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Crosshift Vibrometry: Biomarker for Ergonomic Stress?

by

Edward Jeffrey Klinenberg

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A dissertation submitted in partial satisfaction of the

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Abstract

Crosshift Vibrometry: Biomarker for Ergonomic Stress?

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Doctor of Philosophy in Environmental Health Sciences

University of California at Berkeley

Professor Robert Spear, Co-Chair

Professor David Rempel, Co-Chair

Identification of a reliable and sensitive bioma[illegible] ergonomic stress would be important for the early identification of high risk tasks that may lead to the development of carpal tunnel syndrome. This dissertation consisted of three field studies conducted at a large aircraft repair facility which looked into the use of multi-frequency vibrotactile thresholds changes over the workday (crosshift vibrometry) as a potential biomarker for ergonomic stress. In the first study, 121 industrial workers (82 male, 39 female) from a variety of occupations had their vibrotactile thresholds measured at four frequencies (31.5 Hz, 125 Hz, 250 Hz, 500 Hz) in the morning and afternoon. Fingertip skin temperature, demographic information, time of test, hand/wrist pain, and task information were recorded for each worker. Overall, vibration sensitivity increased as the day progressed. The effect was small and frequency dependent with higher frequencies producing greater effects (0.1 dB @ 31.5 Hz; 1.7 dB @ 500 Hz). Crosshift vibrometry was significantly associated with fingertip skin temperature differences and exposure duration, but only at the highest frequencies (250, 500 Hz). Crosshift vibrometry was not associated with sex or age at any frequency. In the second study, 52 workers from five shops (36 male, 16 female) were tested on two separate days. At the lowest frequency tested (31.5 Hz), crosshift vibrometry was associated with the shops that employees worked in (sheetmetal repair, engine repair, grocery scanners). To evaluate this effect further, a pilot study

involving 16 workers, three shops, and a newly designed electrogoniometer was used to continuously monitor worker wrist position during the shift along with crosshift vibrometry measurements. The results of the pilot study indicated crosshift vibrometry was significantly associated with a number of factors. Vibration sensitivity decreased with sustained ulnar deviation, rapid wrist movement and increased with slow full-ranged wrist motion centered around neutral posture. However, further research and refinements of testing techniques will be needed before crosshift vibrometry can be considered a biomarker for ergonomic stress.

Robert C. Spear

DEDICATION

To my wife Andrea and our unborn child. You should be happy this was completed before you were born.

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Planning, developing, and executing a project of this type would not have been possible without the help of many people along the way. While I wish I could individually thank everybody, I would especially like to thank the following people for their support and dedication on this project. I could not have completed this study without your help:

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I. INTRODUCTION

Within the last decade, the number of work related disorders attributed to cumulative trauma or repetitive motion has been increasing. The Bureau of Labor Statistics (1993) reported 62% of private industry workplace illnesses in 1992 were due to repetitive-stress injuries or cumulative trauma disorders (CTDs). CTDs cases constituted 4.1% of all occupational injuries and illnesses. CTD incidence rate was 36.8 per 10,000, up from 29.7 in 1991.

A commonly diagnosed CTD is Carpal Tunnel Syndrome (CTS). The carpal tunnel is a narrow channel where finger flexor tendons and the median nerve pass. The dorsal floor of the tunnel is formed by a concave arch of carpal bones (covered by intrinsic and extrinsic palmar wrist ligaments. The volar roof of the canal is formed by the transverse carpal ligament.

CTS is attributed to median nerve entrapment within the carpal tunnel. It has been linked to occupational and non-occupational factors including certain extreme hand and wrist positions, tenosynovitis, hypothyroidism, traumatic injuries, rheumatoid arthritis, oophorectomies, diabetes mellitus, or pregnancy (Phalen, 1972, Cannon and Bernacki, 1981, Silverstein and Fine, 1979, Armstrong and Chaffin, 1979, Mulder, 1961, Armstrong, 1983). Symptoms include pain, numbness, and tingling in parts of the hand innervated by the median nerve. Carpal tunnel syndrome can be progressive and often leads to compensable hand disabilities. The exact pathophysiology of CTS is still unknown. Current research indicates it may be due to mechanical compression, ischemia, or a combination of the two factors (Lundborg and Dahlin, 1992).

Short-term changes in vibratory thresholds have been observed among workers using power tools and other intense vibratory sources (Lundstrom, 1986: Harada and Griffin, 1991). Changes have also been observed in people with cold hands (Green, 1977; Weitz, 1941; Verillo and Bolanowiski, 1986). However, no study has looked into the short-term effects of ergonomic stress on short-term changes in vibrotactile thresholds. Crosshift changes (difference between afternoon and morning measurements) are an example of short-term changes applicable to the workplace environment.

One of the newer techniques being proposed for CTS early detection is vibratory sensory threshold testing conducted over a variety of frequencies between 8-500 Hz. Typically, in the early stages of CTS, the peak threshold between 125 and 250 Hz is decreased (Lundborg, 1986). In advanced CTS, the vibration threshold is severely impaired at all frequencies, with the greatest decrements seen in the high frequency range.

In addition to vibrometry's potential role as a diagnostic tool, this study would explore the use of vibrometry as an exposure assessment tool in industry. That is, a biological marker (or "biomarker") of ergonomic stress. Ergonomics stressors, in the context of this study, are factors within a job which can ultimately lead to development of cumulative trauma disorders. Silverstein, et. al (1986)., found high forces (>4 kg average hand force) and high repetition rates (cycle time of less than 30 seconds or more than 50% of the cycle time involved performing the same kind of fundamental cycles) posed the greatest risk for development of CTS. Repeated exertions with a flexed or hyperextended wrist, pressure at the base of the palm or wrist, and low frequency hand arm vibration may also contribute to CTS development (Silverstein and Fine, 1979, Armstrong and Chaffin, 1979). In particular, two questions are posed related to the usefulness of this device as a biomarker for ergonomic stress:

(1) Does short-term exposure to hand intensive jobs cause temporary changes in vibratory sensory threshold levels in workers?

(2) Are specific cumulative wrist postures (extension, flexion, ulnar deviation, and radial deviation) and wrist motions (dynamic and static) related to short-term changes in worker vibratory threshold levels?

II. LITERATURE REVIEW

A. Early Detection of CTS in an Occupational Setting

There are currently no widely accepted diagnostic techniques for the early detection of CTS in an occupational setting. Nerve conduction studies serve as a gold standard for CTS evaluation; however, the test is not suitable for surveillance of large populations; is expensive to conduct (approximately \$500-\$750); somewhat uncomfortable (if not painful); requires the use of highly skilled technicians; and may not detect the early forms of CTS. Nerve conduction studies may produce false-negative results ranging from 5% to 27% depending on the method and normal values selected by the tester (Phalen, 1970, Kimura, 1979, Stevens, 1987).

Other techniques are also being used in the diagnosis of CTS. In general, CTS is a clinical diagnosis based on paresthesias in the median nerve distribution of the involved hand; however, physical findings must confirm the subjective symptoms (Omer, 1992). Traditionally used tests include Phalens test (Phalen, 1966), median nerve percussion (Gelmars, 1979), Semmes-Weinstein monofilaments (Levin et. al., 1978, Weinstein, 1993), two-point discrimination (Morberg, 1958) and vibrotactile threshold measurements (Bleeker and Agnew, 1987, Dellon, 1980). The range of specificities and sensitivities of these tests varies. For example, a literature review by Moore (1992) reported Tinel's sign sensitivity ranged from 44%-63% (specificity 55%-94%) while Phalen's test sensitivity ranged from 71%-75% (specificity 47%-80%). Sometimes, these tests are used in combination to increase the overall sensitivity and specificity (Borg and Lindblom, 1988, Koris et. al. 1990). However, Katz et. al. (1991) demonstrated no single test or combination of tests could offers sensitivities and specificities over 70%.

From the viewpoint of secondary prevention, it is desirable for a CTS screening test to have high sensitivity at the earliest possible detection point. Vibrotactile threshold measurements have shown promise in this area (Rempel et. al., 1992). The test is non-invasive, painless, inexpensive, and easily administered to large groups of people,. The next section looks at the current literature involving use of vibrotactile testing for the detection of CTS.

B. Vibrotactile Threshold Testing for CTS

1. Physiology

There are approximately 17,000 mechanoreceptors in the glabrous skin of the human hand (Johansson and Vallbo, 1979). About 56% of these units are fast adapting (FA). The FA units react only to the onset and cessation of a particular stimulus.

Vibrotactile threshold testing for CTS is a psychophysical test which measures the threshold response of two types of fast adapting sensory mechanoreceptors (Meissner's corpuscles (FAI) and Pacinian corpuscles (FAII)) in the glabrous skin of the fingertips and the corresponding sensory fibers (Aβ, approximate diameter 6-12 μm, approximate conduction velocity 36-72 m/sec). The two mechanoreceptors operate at two different, but overlapping, frequency ranges.

The FAI units are most sensitive to low-frequency sinusoidal mechanical stimuli (5-50 Hz centered approximately around 30 Hz) while the FAII units are most sensitive to high-frequency sinusoidal mechanical stimuli (50-300 Hz centered approximately around 250 Hz) (Kanel et. al., 1991, Lundstrom and Johansson, 1986). The excitation of Meissner's corpuscles is felt as a gentle fluttering in the skin. This sensation is well localized reflecting the small size (between 3 and 50 mm^2) of the receptive field and topical location of each Meissner corpuscle (Johansson and Vallbo, 1983).

In contrast, the excitation of Pacinian corpuscles evokes a diffuse, humming sensation in the deeper tissue which is not well localized. The receptive field of a Pacinian corpuscle is much larger and can include an entire finger (Johansson and Vallbo, 1983). The Pacinian corpuscles are also located deeper in the skin than the Meissner corpuscles.

The distribution of Meissner corpuscles to Pacinian corpuscles in the fingertip is not even. The Meissner corpuscles have a 25 times greater innervation density than the Pacinian corpuscles (Johansson and Vallbo, 1983). By activating these two mechanoreceptor units, humans are capable of discriminating vibrations between 5 and 500 Hz.

Vibrotactile threshold testing can be conducted in a variety of ways. The three most common methods being used today are tuning forks, single frequency vibrometers, and multi-frequency vibrometers. All three methods are being explored as early detection tools for CTS.

2. Tuning Forks

The most common tuning forks used for assessment of CTS have frequencies of 30 Hz and 256 Hz (Bell-Krotoski et. al., 1988, Dellon, 1983). The test consists of striking the tuning fork against a firm object and placing the vibrating tip tangentially against the fingertip. Several digits on both hands are tested and the test is considered positive when the patient can qualitatively recognize differences in vibration levels between digits.

Gelberman et. al. (1983) used a tuning fork at 256 Hz to monitor the fingertip vibration threshold changes in 12 healthy volunteers (both sexes) exposed to artificially induced carpal tunnel pressures of 40, 50, 60, and 70 mm Hg. Tissue pressures were monitored using a wick catheter and maintained for 30 to 240 minutes. Compression was terminated either 10 minutes after a complete sensory block had occurred or following 180 to 240 minutes of compression resulting in no more than a 25 per cent reduction in sensory amplitude recording or significant symptoms of nerve compression. Sample size for this study was small (two subject @40 mm Hg, two subjects @50 mm Hg, three subjects @60mm Hg, one subject @70 mm Hg, and two subjects at both 40 and 50 mm Hg).

The tuning fork was placed tangentially on the fingertip. A change in vibration threshold was noted when the subject could differentiate the vibration levels between the same fingertip on both hands. For comparison purposes, two-point discrimination (static and moving), Semmes-Weinstein monofilament, sensory and motor conduction velocity testing, motor strength measurement of the abductor pollicis brevis, and subjective patient comments were also taken during the test period.

Vibratory threshold changes were noted at all levels of compression. At 40 mm Hg, altered vibratory perception was recorded for 75% of the subjects after a maximum of 240 minutes of forced compression. At 50 mm Hg, altered vibratory perception occurred for 100% of the subjects approximately 25-40 minutes after initial compression. The loss of vibration sensation was directly linked to the onset of paresthesias. For pressures of 60 and 70 mm Hg, all normotensive subjects demonstrated increased vibratory threshold levels within 20 minutes of compression. All induced vibratory threshold changes immediately returned to normal after decompression.

Through this study, Gelberman et. al. demonstrated vibratory threshold changes correlated closely with electrophysiological changes during the artificial nerve compression. Vibratory threshold changes also correlated well with the onset of parathesias. However, the authors commented that their results may apply only to relatively short time periods (i.e. four hours or less). This point is crucial since the potential workplace exposure can be eight hours or more.

A companion study by Szabo et. al. (1984) evaluated the vibration sensitivity of twenty subjects (23 hands) who underwent carpal tunnel release. Again, a 256 Hz tuning fork was used to measure vibratory sensitivity changes. In addition to the tuning fork, a single frequency vibrometer was also used. The vibrometer results will be discussed in a later section.

Preoperatively, twenty hands (70% of the total) had vibration sensitivity deficits in their affected hand. Nine hands of nine patients were evaluated at a time period from one to five days after surgery. While eight of the nine still had abnormalities, 63 percent of the subjects improved their perception from preoperative levels. After six weeks, 81 percent of the subjects improved their vibration sensitivity from pre-operative levels. However, none of the hands returned to "normal" after the six weeks. The authors concluded this delay in full recovery was related to the severity of the nerve injury at the time of decompression.

Dellon (1983) also used tuning forks (30 Hz and 256 Hz) and a single frequency vibrometer to assess their ability to identify various degrees of CTS. Thirty four hand and three CTS severity classifications (early, moderate, severe) were used. The early CTS classification consisted of positive Phalen's sign, positive Tinel's test or hypersensitive vibratory perception. The moderate CTS classification added decreased vibratory perception to a tuning fork or muscle weakness. Finally, severe CTS was defined by persistent sensory symptoms, abnormal two-point discrimination, or muscle wasting.

The results were interesting. Some increased vibration sensitivity changes were noted for all hands in the early CTS group. Twenty eight percent of the hands showed increased vibration sensitivity at 30 Hz while forty two percent showed increased vibration sensitivity at 256 Hz. The number of hands having increased sensitivity decreased dramatically for the moderate and severe CTS groups.

Meanwhile, the percentage of hands showing diminished vibration sensitivity increased. For the severe CTS group, 84% (@30 Hz) and 100% (@256 Hz) had decreased vibration sensitivity. From these results, Dellon concluded the earliest clinical finding of peripheral nerve compression is a hypersensitive response to vibratory stimulation.

Tuning forks are simple to use, lightweight, and cheap. However, they do have some significant drawbacks. A tuning fork is an uncontrolled stimuli (Bell-Krotoski, 1988). The actual amplitude of the signal is dependent on the initial force provided by the tester (i.e. how hard to hit the tuning fork on a hard surface), and the application of the vibrating tuning fork to the skin. Wide variations between testers can be expected.

Tuning forks also do not necessarily provide a pure frequency stimulus. The strength and frequency of the harmonics and subharmonics generated may be strong enough to activate both slowly and fast adapting mechanoreceptors. Finally, tuning fork results are qualitative in nature. To achieve a more quantitative and repeatable signal for CTS diagnosis, a vibrometer must be used.

3. Single Frequency Vibrometers

Two commercial single frequency vibrometers (Bio-Thesiometer by Biomedical Instruments and the Vibratron II by Physitemp) have been tested for potential applications in CTS diagnosis. Both the Biothesiometer and the Vibratron II operate at 120 Hz. Both instruments are capable of producing controlled sinusoidal vibrations.

The Biothesiometer is a portable handheld unit which consists of a 13 mm diameter rounded plastic surface attached to a vibrator. The vibration output of the Biothesiometer is displayed as voltage and converted to displacement units (micrometers of motion of the vibrating head) using the enclosed calibration chart. A knob on the unit regulates the amplitude of vibration. A vibration sensitivity measurement is usually taken with the tester holding the subjects hand with one hand and manipulating the vibration amplitude with the other hand.

As described earlier, Dellon (1983) compared results from the Biothesiometer and tuning forks on 34 hands with varying stages of CTS. Abnormal vibration thresholds were determined using data from Gregg (1951). The Biothesiometer was unable to detect any vibration sensitivity changes in the early stages of CTS. For moderately severe cases, fifty five percent of the subjects showed vibratory threshold abnormalities. For severe CTS, eighty five percent of the subjects showed severe threshold abnormalities. Dellon concluded the vibrometer added no new information over existing sensibility tests. However, he also concluded vibratory threshold data could provide objective, quantitative follow-up information for patients studied longitudinally.

The previously described study by Szabo et. al. (1984) also included testing with the Biothesiometer in addition to tuning fork data. In this case, eighty seven percent of the preoperative CTS diagnosed hands showed abnormal vibratory thresholds. After six weeks postoperatively, eighty five percent of the hands had improved vibratory threshold levels. Forty percent had returned back to normal vibratory threshold levels.

While not specifically looking for CTS, Wiles et. al. (1990) used a Biothesiometer with the aim of developing accurate normal age adjusted tables for vibration perception thresholds (VPTs). Thirteen hundred sixty five subjects of both sexes, various ages, and occupations were measured over both thumb pulps, toes, and ankles. The VPT readings were taken at each site with the lowest of the three used for the study.

The age adjusted study showed the left thumb have a consistently lower VPT than the right thumb. The effect was more pronounced in men than women. However, the difference in VPTs between hands in men could be explained almost entirely by one of the subgroups (factory workers). These differences were not noted in the toes or ankles. Based on these results, the authors concluded the results are related to repeated mild trauma affecting the right hand more than left during daily activities (work or otherwise).

The Vibratron II consists of a controller unit and two identical testing posts. Each post is plastic and 1.5 cm in diameter. As with the Biothesiometer, the amplitude of vibration is determined by the applied voltage. Unlike the Biothesiometer, the subject places his/her hand on the fixed probe. The applied voltage is adjusted manually by the user. The amplitude of vibration of displayed in "vibration units" ranging from 0-20. These vibration units can be converted to log microns of peak-to-peak displacement using an appropriate formula (Gerr et. al., 1991).

Grant et. al. (1992) used the Vibratron II in an attempt to detect CTS in an industrial setting. A total of 132 female participants (252 hands) participated in the study. The females came from a variety of clerical and industrial jobs. Four groups were established for comparison (control (no CTS symptoms), at-risk (no CTS symptoms), at-risk (CTS symptoms), diagnosed CTS). A hand diagram filled out by the user was used to categorize subjects in the at-risk group.

Vibration threshold measurements were conducted on the third and fifth digits of each hand using a two-alternative, forced choice psychophysical method (Arrezo, 1982). The vibration thresholds measurements in the third digit were statistically significantly lower in the CTS group compared to the non CTS group. No significant differences between the third and fifth digits were noted.

However, the Vibratron II was unable to distinguish between the group(s) exhibiting CTS symptoms and those with no CTS symptoms. The authors concluded this inability to measure differences between the working group with symptoms and the control group was evidence that the Vibratron II was insensitive to early CTS development. At approximately the same time of this study, work by Jetzer (1991) indicated multi-frequency vibrometry had the capability to distinguish between workers with and without symptoms.

A similar study was performed by Franzblau et. al. (1993). Besides vibrometry measurements using the Vibratron II, subjects were given a questionnaire survey, limited physical examination of the upper extremities, limited electrodiagnostic testing, two-point discrimination, palmar pinch strength, and hand grip strength tests. A vibratory threshold was considered abnormal if it was 1.65 standard deviations below published normals based on age and height (Gerr et. al, 1990). The vibratory threshold was calculated using the method of limits procedure and averaging over three vibration disappearance thresholds (VDTs) and vibration perception thresholds (VPTs) per subject.

All subjects were workers at an auto parts manufacturing plant. A variety of job classes including assembly workers, maintenance workers, front office workers, and management personnel were included. An ergonomic assessment of the assembly line was made using video cameras and visual observations. Little difference in hand motions was noted.

A total of 130 subjects participated in the study. Of these 130 subjects, thirty five had a least one finding from the physical examination related to CTS. In contrast, only 10 subjects had abnormal vibration threshold readings. Sensitivity of the vibrometer alone to detect CTS was the poorest among the quantitative tests used in the study. The authors concluded from this study that quantitative test procedures including vibrometry add little additional information to a symptoms survey when screening subjects in the work setting.

An additional device, called the Optacon, was used by Winn and Biersner (1994) to compare vibrotactile thresholds in subjects with and without CTS. The Optacton is not a vibrometer per se. Rather, it is a matrix of 144 rods vibrating at the same frequency (230 Hz) with each rod having a different amplitude. The subject moves from rod to rod in a forced-choice psychophysical method. The rods are spaced two mm horizontally and one mm vertically. Amplitude is measured in voltage units from .5 V to 6.5 V. In this study, a white masking noise was used to mask sounds from large amplitude vibrations.

Twenty seven subjects with CTS and 34 controls participated in the study. Subjects were classified into four age groups (20-29, 30-39, 40-49, >49). CTS cases were confirmed by a neurologist using a standardized definition. However, it was unclear in the paper if all CTS cases were bilateral. No ergonomic exposure information was provided in the paper. Sex was not considered as an independents factor. Hand temperature was not directly measured. Rather, the ambient room temperature was controlled to maintain subject's hand temperature above 33° C. Vibration thresholds were measured on the second and fifth digits of both hands. Nerve conduction studies were also measured for the left and right hands.

For the median nerve, the authors reported significant differences ($p<.05$) between control and CTS confirmed vibration thresholds in all age groups and for both hands. For the ulnar nerve, the authors reported significant differences between control and CTS confirmed vibration thresholds in the left hand only. The authors also report the vibration threshold results closely parallel the nerve conduction sensory amplitude testing. From the data, the authors conclude a) vibration threshold testing is comparable to nerve conduction testing in differentiating controls from CTS, and b) vibration threshold testing have been validated against sensory amplitude component of nerve conduction testing and may identify an underlying peripheral nerve effect that leads to vibrotactile threshold changes.

4 Multi-Frequency Vibrometers

Multi-frequency vibrometers expand the idea of mechanically controlled vibration inputs to multiple frequencies. McQuillan (1970, 1971) described a multi-frequency system to monitor vibration sensitivity after median nerve repair. Two commercial units (Automated Tactile Tester by Topical Testing and the Vibrometer by Bruel and Kjaer) are currently being tested and marketed for their application in CTS diagnosis. These systems are also computer controlled.

The Automated Tactile Tester (ATT) is actually a series of components including a thermal stimulator, a force-controlled probe for testing sensitivity to pin-prick, a displacement-controlled probe for touch sensitivity testing, and another module for two-point discrimination (Horch et. al., 1992). The vibrometer portion of the unit consists of displacement-controlled actuator with a one mm diameter blunt-tipped probe. The probe can deliver controlled frequencies from 0 to 250 Hz. The authors contend thresholds are not significantly affected by changes in the skin/stimulator interface as long as a light touch is used.

Vibration thresholds are determined incrementally using a staircase methodology in which both VPTs and VDTs are determined. Vibration thresholds are defined as the average amplitude (in micrometers) of the VPT and VDT. Testing is conducted in a pronated position.

Using this device, Hardy et. al. (1992) evaluated 61 subjects with CTS symptoms, but no prior record of nerve injury or surgery. Both hands were tested only if the subjects had bilateral symptomology. The vibration thresholds were measured on the 2nd and 5th digits using two frequencies (50 Hz, 150 Hz). Subjects were classified as normal or abnormal based on the 99th percentile limits established for the system (Horch et. al., 1992).

Of the initial 61 subjects, 31 subjects (40 fingers) had independently confirmed abnormal conduction velocities. The 150 Hz vibration threshold alone identified approximately 57% of this group. The 50 Hz vibration threshold alone identified approximately 68% of the same group. The use of both 150 Hz and 50 Hz did not increase the percentage above 68%. From this data, the authors concluded low frequency vibration is an early indicator of nerve compression.

A follow-on study was conducted by Jimenez et. al. (1993) looked at the testing parameters most sensitive to sensory loss in CTS. Twenty four subjects who had clinical symptoms consistent with CTS were included in these study. Subjects also reported no previous peripheral nerve injury or surgery. Vibration threshold testing was conducted both with the Biothesiometer (120 Hz) and the ATT (50 Hz only). The second, third, and fifth digits were tested. Testing was conducted preoperatively (24 subjects) and at six weeks (19 subjects), three months (19 subjects), and six months (17 subjects) postoperatively. Various types of carpal releases were performed.

The results indicated the abnormal 50 Hz vibration levels were recorded in the middle finger for approximately 85% of the subjects prior to surgery. After surgery, the number of abnormal vibration threshold decreased to 63% (six weeks). Then, the abnormal vibration thresholds rose to 70% (three months) and seemed to stabilize at 72% (six months).

Abnormal vibration thresholds at 120 Hz were note for approximately 33% of the subjects preoperatively and gradually declined to 20% by six months. There was no statistical difference between vibration thresholds of the middle and index finger preoperatively. The authors also calculated the normalized median values for 50 Hz vibration thresholds. For the middle finger, the normalized median values started at 2.4 preoperatively and decreased to 1.1 after six months. From this data, the authors concluded 50 Hz vibration thresholds was the best frequency to track median nerve sensory loss and recovery following surgery.

The vibrometer was developed by modifying a Bekesy-type audiometer to operate within 8-500 Hz. A full description of the unit is contained later in this paper. In short, the headphones from a Bekesy-type audiometer were replaced by a vibration exciter with a 5 mm^2 tip mounted on top. With this device, any number of frequencies could be tested.

Each frequency is tested at a user specified period of time. Unlike other vibrometers, vibration sensitivity thresholds are reported in decibels of acceleration (ref. 10^{-6} m/sec^2).

Lundborg et. al. (1986) first demonstrated the possibilities of the vibrometer in identifying early signs of CTS. The authors compared vibrogram results from a control group (55 subjects) of various ages and occupations to 76 subjects (132 hands) who complained of typical CTS symptoms. Electromyograms of the abductor pollicis brevis muscle and sensory nerve condition measurements were recorded for 79 of the CTS symptomatic cases. Surgical decompression was performed on 46 cases. For this group, vibrograms were repeated postoperatively two weeks, two months, and six months.

Vibrograms were taken for each hand (both 3rd and 5th digit) at seven frequencies (8, 16, 31.5, 63, 125, 250, 500 Hz). The frequencies were tested in a sequentially increasing order. The subject identified the VPTs and VDTs through use of a handswitch. By pushing and holding the handswitch, the subject was able to reverse the direction of the vibration stimulus. The vibration sensitivity threshold for each frequency was taken as the average of the VPTs and VDTs. The subject was tested in a pronated position and allowed a preliminary test for practice purposes.

This author's reported a typical shape for a normal vibrogram. The normal vibrogram consisted of fairly constant vibration thresholds in the lower frequencies (8, 16, 31.5, 63 Hz), followed by a slight increase in vibration sensitivity (lower thresholds, 125, 250 Hz), and a sharp drop-off in vibration sensitvity (higher threshold) at the highest frequency (500 Hz). The shape of the curve remained constant for the two age groups (<45 years and >45 years).

The authors also found the CTS symptomology group could be broken down into three stages. Stage I was characterized by the flattening of the curve (increased vibration sensitivity thresholds) at 125 or 250 Hz. This change did not correlate with any weakness in the abductor pollicis brevis muscle. A few subjects did complain of pain at night, but this was not evident during a medical examination.

In stage II, the changes in vibrogram shape become more evident. Higher frequencies become increasingly difficult to perceive and some loss in the lower frequencies was evident. At stage III, vibration sensitivity thresholds for the highest frequencies (250, 500 Hz) were above the machine's capabilities. Further loss of sensitivity was clearly evident in the lower frequencies. These changes correlated with increased symptomology in patients. Of the 53 cases which were diagnoses as CTS, the vibrogram was abnormal in 44 cases (83%).

The changes in vibrometry after carpal release were dependent on the subject's condition prior to surgery. In cases with only intermittent symptoms (parathesia and numbness), the vibrogram usually returned to normal. The time to return to normal varied from several weeks to months. For more advanced cases of CTS, the authors reported no normalization of the vibrogram even after six months. The author's explained the differences based on the mechanism involved (ischemia versus mechanical compression with subsequent myelin damage).

Jetzer (1991) used a vibrometer to demonstrate its effectiveness in identifying early signs of CTS. In Jetzer's study, four different groups were evaluated using a questionnaire and vibrometry. The four groups included 39 assembly workers, 100 meat processors, 284 keyboard operators, and 284 controls. The group of workers were classified by level of ergonomic risk (force, repetition, awkward posture). All controls and many of the exposed group with symptoms received a physical examination. Only individuals with confirmed cases of CTS (by electromyography or recent surgery) were considered to be positive for CTS in the study. Subjects with CTS symptoms were analyzed separately.

All vibrograms were conducted on the third digit of each hand. All subjects were trained on the technique prior to formal testing. Testing was conducted at the beginning of the shift or after a period away from strong vibrations or cold. Jetzer used the same protocol as Lundborg et. al. (1986).

Jetzer, however, evaluated the vibrograms in a different manner. Instead of looking at vibration sensitivity threshold at each frequency, Jetzer used a cumulative scoring technique (Jetzer and Conrad, 1987). The technique involved adding up the number of 10 dB increments (or fraction thereof) between the subject's vibration threshold (at each frequency) and 160 dB (the limit of sensitivity of the vibrometer). Three groupings were developed from this type of scoring technique. A vibrometry score over 30 was considered normal. A vibrometry score below 20 was considered abnormal. Scores between 20 and 30 were considered borderline abnormal.

Jetzer's result indicated a statistically significant differences in the vibrometry scores between a) exposed and control groups, b) symptomatic and non-symptomatic subjects, and c) confirmed CTS and non-symptomatic subjects. Vibrograms taken on a subsection of the assemblers after six months and no ergonomic intervention revealed similar vibrogram results. Jetzer concluded from these results that vibrometry is useful as a screening tool for CTS.

Conrad et. al. (1993) has been evaluating the usefulness of vibrometry screening in a small size prospective cohort. The cohort consisted of 20 dental hygiene students entering initial training in 1986. Vibrograms were taken initially on the students entering the program, three times a year during training (fall, winter, spring) and annually after graduation (1988). Jetzer's scoring method was used for the vibrograms.

The authors reported a statistically significant threshold shift (low vibrometry scores) during the first year after graduation. However, this threshold shift had arrested by the end of the second year. By the third year after graduation, the sample size was reduced to 16.

At the three year point, no dental hygienist had developed CTS. Two hygienists had abnormal vibrometry scores. The mean vibrometry scores for the dental hygienist began to drop significantly compared to the previous year. However, the overall mean vibrometry scores were still within normal limits. The authors could not conclude this threshold shift was the onset of CTS in the hygienists.

Neese and Konz (1993) used vibrometry to understand if repetitive jobs differed from those in non-repetitive jobs. One hundred sixty five workers and supervisors were used. CTS symptomology from each worker was obtained by questionnaire (pain, pain at night, CTS diagnosis, and numbness). Repetition, force, pace (self or machine) and awkward posture were obtained by questionnaire and observations. Ergonomic factors were scored on an analog scale from zero to ten.

A series of linear regression models were performed to establish relationships between ergonomic factors, CTS symptomology, and vibrometry scores. Vibrometry scores were developed using Jetzer's technique for all seven frequencies, top three frequencies (125, 250, and 500 Hz), and the top two frequencies (250 and 500 Hz). Machine pace was the best single predictor of vibrometry scores. However the R^2 was small (13.7-14.4%)

depending on the scoring technique). Combining pace with reports of pain and age increased the R^2 values slightly (23.5-24.3%). It was uncertain if the author's conducted a F test to remove to determine the statistical significance of adding an additional variable to the model.

The scores developed from just the top two frequencies gave the highest R^2 values in the model. Based on these results, the author's concluded the majority of information in the vibrogram is contained in the higher frequencies. The authors concluded use of fewer frequencies will simplify the test and potentially make it cheaper to implement.

Lundborg et. al. (1992) used a different type of scoring method coined "the sensibility index" for evaluation of CTS. The purpose of the sensibility index was to attempt to quantify shape differences in vibrograms during various stages of CTS. The sensibility index was defined as the area under a seven frequency vibrogram (maximum vibrometer limit 150 dB) divided by the area under an age adjusted reference vibrogram (Lundstrom et. al., 1992). A sensibility index of .8 or less was considered abnormal.

The sensibility index was calculated from vibrograms obtained from 300 patients with various types of neuropathies. Of these 300 patients, forty five were diagnosed with CTS. Seventy three percent of the patients in the study had abnormal vibrograms in two or more fingers (not necessarily the same two fingers). Abnormal vibrograms of the median nerve of one hand only occurred in 22% of the patients.

From this data, the authors concluded the sensibility index was a valuable tool for assessment of sensory dysfunction when used in combination with other appropriate clinical data. The authors still felt qualitative review of the shape of the vibrogram curve may be needed to help refine the diagnosis. The authors hypothesized the low percentage of abnormal vibrograms in one nerve (but higher in all nerves) was the result of generalized increase in endoneurial fluid pressure.

Burastero et. al. (1993) compared the usefulness of vibrometry to nerve conduction studies in the diagnosis of CTS. Thirty nine subjects (60 hands) with electrophysiologically confirmed CTS had vibrograms conducted on their affected hands using the previously described protocol. Their results indicate a diagnostic sensitivity of 88%. However, the authors concluded the technique lacked the specificity of nerve conduction, needed appropriate cutoff points, and must be combined with clinical findings.

Overall, changes in vibration sensitivity do seem to correspond to changes in CTS stages. However vibrotactile threshold measurements can be affected by a variety of factors in addition to occupational exposure. The next section gives a review of these issues.

C. Vibrotactile Threshold Measurement Issues

Vibrotactile threshold measurements are dependent on the entire somatosensory pathway. This includes the mechanoreceptors, peripheral nerves, and higher order processing functions in the brain. Therefore, changes in any of these areas may be manifested as altered vibrotactile threshold measurements. The following is a review of factors which may confound crosshift vibrometry measurements in the upper extremities.

1. Test Protocol Methodologies

Vibrotactile threshold testing comes in basically two forms: forced choice and Yes-No protocols. In a forced choice method, the subject must identify the stimuli presented in two or more intervals within each trial. The location of the stimuli usually changes from trial to trial. Stimuli is typically presented using the staircase method (Cunonomy and Barnes, 1976). The Vibratron II and Automated Tactile Tester are examples of commercial units which advocate use of this technique.

The Bruel and Kjaer vibrometer uses a Yes-No protocol. In a Yes-No protocol, the subject must identify when the stimulus is felt or not. The stimulus is typically presented using the method of limits (Lundborg et. al. 1986). Under the method of limits, a monotonically increasing or decreasing stimulus is presented to the subject. The rate of increase of the stimulus varies. In the Biothesiometer, the rate is dependent on the operator controlling the manual dial. With the Bruel and Kjaer vibrometer, a computer controlled constant logarithmic acceleration increase (in dB) is used. Dyck et. al. (1990) used a constant exponential displacement increase based on a previous estimate of just noticeable differences.

The method of limits has been shown to be quicker and just as reliable as the forced-choice methodology (Gerr and Letz, 1988, Dyck et. al., 1990). However, the method does have a few potential drawbacks.

First, there is a possibility of a criterion shift bias (Gerr and Letz, 1993, Bove et. al., 1986) in the vibrotactile threshold measurement during various tests on the subject. Second, by increasing the stimulus rates, vibrotactile thresholds can be overestimated (though repeatable) (Dyck et. al., 1990) compared to slower stimulus rates. Third, method of limits may be difficult to administer with subjects complaining of parathesia. Finally, Dyck et. al. recommended using forced-choice methodology if subjects responded to vibration during a null stimulus.

2. Use of Surround and Varying Finger Forces

Harada and Griffin (1991) looked at the effects of surrounds, finger contact force on vibrotactile thresholds. Combinations of surrounds around the seven mm diameter vibrating tip (none, 1.5 mm gap, 3 mm gap) and contact force applied by the finger (1N, 2N, or 3N). Five subjects were tested using the left middle fingertip. Six separate frequencies (16, 31.5, 63, 125, 250, 500 Hz) were evaluated for vibrotactile thresholds under the various surround and force conditions. The protocol used by the authors to measure vibrotactile thresholds was not mentioned even though the results were reported in acceleration levels (m/sec^2).

The authors reported statistically significant effects from the surround. Furthermore, these effects were frequency dependent. At low frequencies (16, 31.5 Hz), use of a surround resulted in increased vibrotactile sensitivities (15-20 dB). At higher frequencies (125, 250, 500 Hz), use of a surround resulted in a less pronounced decrease in vibrotactile sensitivities (2-5 dB). No statistical difference was noted at 63 Hz.

Contact force results were also frequency dependent. Borderline statistical differences in contact forces were seen only at the higher frequencies (125, 250, 500 Hz). At the highest frequencies, differences between the highest and lowest contact force ranged from 2-6 dB.

In an experiment involving the vibrometer, Lundstrom et. al. (1992) performed vibrograms on 171 healthy males using two different measurement protocols. One protocol precisely controlled fingertip pressure to 3.5 N/m^2. The other protocol relied on the subject placing their finger on the vibrating probe. Approximately 40% of the subjects were tested using controlled fingertip pressure. No statistical differences in the two protocols could be found.

3. External Vibration Effects

Potential temporary threshold shifts in vibrotactile sensitivities by strong vibratory sources were also explored by Harada and Griffin (1991). The author's required each subject to grasp a vibrating handle (31.5, 63, 125, 250, 500 Hz) at 10% maximum grip strength for five minutes and then monitored the change in vibrotactile thresholds immediately, thirty second (interpolated if not directly measured), two minutes, five minutes, ten minutes, and 20 minutes after exposure. Three frequencies of vibrotactile thresholds were measured for each frequency of vibration exposure. A control trial where subjects grasped the handle without vibration exposure was also conducted.

At the 30 second post exposure period, significant increases in the vibration sense threshold were reported. Threshold changes were highest at the highest frequencies (125, 250, 500 Hz). The threshold change ranged from 12 dB - 28 dB. The highest threshold changes occurred for exposures in the 125 and 250 Hz range.

At the lower frequencies (16, 31.5 Hz) threshold changes were less ranging from 4 dB to 12 dB. The highest threshold changes occurred for exposures in the 16 and 31.5 Hz range. Oddly, the authors never published data concerning recovery from vibration after 30 seconds.

Harada and Griffin's data confirmed earlier results obtained by Lundstrom and Johansson (1986). In their study, the authors used a two minute vibration stimulus at 2, 20, and 200 Hz along with a method of limits protocol. Vibrations were delivered to specific receptive fields using a six mm diameter cylindrical probe with a constant one mm skin indentation. Besides showing an initial temporary threshold shift, Lundstrom and Johansson demonstrated complete recovery from the vibration effects within a few minutes of exposure.

4. Age and Reliability

Besides measuring contact force pressures, Lundstrom et. al. (1992) also looked into the effects of age and uncertainty intervals of a vibrotactile measurement when developing a reference population for the vibrometer. The standard methods of limits vibrogram protocol was used for all measurements (i.e. seven frequencies, 3 dB/sec constant ramp rate). The independent effect of age on vibrotactile thresholds was shown to be significant for all frequencies tested. A roughly .3 dB per year decrease in vibrotactile sensitivity at the higher frequencies (≥125 dB) and .1 dB per year at the lower frequencies (<125 dB) can be expected from age 20 on. The overall R^2 were low for this relationship (.02-.15) with the higher R^2 occurring at the highest frequencies (250, 500 Hz). These results are consistent with other authors data (Halonen, 1986, Gerr et. al., 1990, Goldberg and Lindblom, 1979).

The uncertainty interval for each individual was defined by the authors as the difference between the VPT and VDT. Based on the individual's uncertainty levels, a group mean and standard deviation were determined for each frequency. Given the testing protocol used by the authors, it is assumed the number of measurements that went into the VPT and VDT varied per individual. The overall results indicate the group uncertainty level mean (12.6-13.6 dB) and standard deviation (5.7-6.1 dB) for each test are frequency independent.

The reliability of the vibrogram itself over time was measured by Grunert et. al. (1990). Thirty eight subject (76 hands) were used for the study. Forty four of the hands had symptomology indicative of CTS. Each subject performed a total of six vibrograms (three per hand) with each hand alternated per trial. Each vibrogram was measured over the seven octave band frequencies. VPTs and VDTs were calculated for each frequency and trial. The number of measurements that went into the VPT and VDT varied per individual. Pearson product-moment correlation coefficients were calculated for each frequency and trial pair.

The authors reported VPT correlation coefficients ranging from .518-.861 and VDT correlation coefficients ranging from .516-.871. The authors found the correlation coefficients for both VPT and VDT were best for trials two and three. The reliabilities ranged from .762-.870. The only exception was 63 Hz. Based on these results, the authors concluded a practice trial would result in a more consistent subsequent vibrogram reading.

White et. al. (1994) studied daily variations in vibrotactile sensitivity thresholds of four age-matched women with various stages (none, mild, moderate) of CTS. The four women used keyboards more than four hours daily. A total of 84 vibration sensitivity readings were taken at various times over a three month period. Vibrotactile thresholds were determined using the Vibratron II and the methods of limit technique. Only one VPT and VDT were determined per trail.

For the collected data, the authors calculated 95% confidence intervals for each subject. Using a threshold of 1.5 vibration units to discriminate healthy wrists from CTS wrists, the authors calculated various false-negative and false-positive percentages for each subject. The authors found daily variations in vibrotactile measurements could result is a false negative percentage of 47.6% for the moderate CTS subject and a false positive percentage of 9.5% for the normal subject. The authors recommend multi-day testing to strengthen the predictive value of the technique.

5. Crosshift Vibrotactile Threshold Changes

Very little published information is available concerning crosshift vibrotactile threshold changes. White et. al. (1994) as part of their study did compare morning and afternoon vibrotactile thresholds. The information is incomplete, does not include how many trials made up each the AM and PM data per subject, is made up of a symptomatic and non-symptomatic subject pool, and does not indicate actual time difference between trials. Furthermore, no statistically significant differences in vibrotactile thresholds occurred. However, the authors noted the individual morning thresholds were consistently lower than afternoon thresholds.

Snook et. al. (1994) conducted two experiments involving women simulating repetitive work in a laboratory. In the first experiment, sixteen women with no prior history of CTS by examination and history performed repetitive flexion and extension (at various controlled repetition rates) for 20 total days. The first five days were used for training and not included in the analysis. In the second experiment, fourteen subjects performed only wrist flexion (for 15 times per minute) for 23 days. The first four days were training sessions and not included in the analysis.

Vibrotactile threshold measurements were taken using a 120 Hz vibrometer. A forced choice method was used in the first experiment and a method of limits protocol in the second. Measurements were taken at the beginning, middle (4 hour), and end (7 hours) of the shift for experiment one. For experiment two, measurements were only taken at the beginning and end of the day. For both experiments, mean vibrotactile thresholds decreased (i.e. increased vibrotactile sensitivity) as the day progressed.

6. Temperature Effects

Vibrotactile sensitivity can be affected by skin temperature (Weitz, 1941, Green, 1977, Verillo and Bolanowiski, 1986). The general effect is decreased sensitivity (i.e. increased vibrotactile thresholds) as skin temperature is lowered. The magnitude of the effect is also frequency dependent. Vibrotactile threshold measurements in the higher frequencies ($\geq$ 125 Hz) are more sensitive to temperature effects than lower frequencies.
These studies, however, had low sample sizes, various tests sites and methodologies, and not specifically designed to evaluate the effects of fingertip temperature using the Bruel and Kjaer vibrometer. A pilot study exploring the temperature effects of vibrotactile thresholds on the Bruel and Kjaer vibrometer is presented later in this study.

7. Summary

Many different factors can affect vibrotactile threshold measurements. By reducing (or at least identifying) the impact of these factors, the potential for finding crosshift changes as a function of ergonomic stress can be maximized. The vibrometry testing protocol used in this study was designed to identify, quantify, and test methods to control the impact of these independent factors.

III. PRELIMINARY STUDIES

No previous published data with the equipment used in this study was available concerning short-term vibrometry changes and goniometer measurements in an industrial setting. The vibrometer used in this study had been previously used only for diagnostic purposes in controlled environments while the goniometer was a newly manufactured device. Preliminary qualitative observational studies were conducted to evaluate the potential usefulness of the existing test protocols and data outputs for these devices in monitoring short-term ergonomic exposures in an uncontrolled workplace environment.

These preliminary studies were conducted at various shops at McClellan AFB. Environmental conditions varied from outside to climate controlled offices. One particular factor, temperature extremes, was formally evaluated using a repeated measures design. The results from these preliminary studies served as a basis for protocol modifications in the full-scale vibrometry and electrogoniometry studies described later in this study.

A. Description of Equipment

1. Vibrometer

Vibrotactile threshold testing was conducted in this study using the Bruel and Kjaer vibrometer (Model 9627). The vibrometer is a modified Bekesy audiometer designed to respond within the range of human vibration sensitivity. It consists of a mechanical shaker, armrest, accelerometer, hand switch, five mm^2 test tip, headphones, and data acquisition/control system controlled by an IBM compatible personal computer using software driven menus (Figure 1). Vibrotactile thresholds are measured in acceleration units and expressed in decibels (dB) using the following equation:

$$\text{Vibrotactile Threshold} = 20*\log(a_{rms}/a_{ref})$$

a_{rms} = the root mean square (rms) of the vibration acceleration

a_{ref} = the reference vibration acceleration (10^{-6} m/s^2)

The overall testing procedure is straightforward. The subject is seated comfortably and places his/her arm in the adjustable armrest. The armrest is then adjusted so the subject's fingertip lightly touches the test tip. The use of an accelerometer and feedback loop in the system ensures the sinusoidal accelerations delivered to the fingertip is load independent.

The subject is instructed to keep his/her eyes closed and concentrate on the vibration throughout the test. Headphones (with optional random masking noise) are used to minimize environmental noise exposure. The subject is given a hand switch to hold in the non-dominant hand. The subject is instructed to push and hold the hand switch when he/she feels the vibration and to release the hand switch when the vibration ceases. The vibration level increases by a constant rate pre-selected by the tester.

The procedure generates a sawtooth pattern of accelerations with top peaks being a series of vibration perception threshold (VPTs) and bottom peaks being vibration disappearance thresholds (VDTs) (Figure 2). The test continues for a preselected time at each frequency. A mean and standard deviation is automatically calculated for each frequency using combined VPT and VDT data. The specific number of VPTs and VDTs per frequency varies with the subject and is based on the subject's response to the vibration stimulus.

The Bruel and Kjaer vibrometer offers flexibility for vibrotactile sensitivity testing. Any frequency between 8 and 500 Hz can be selected. Up to 12 separate frequencies can be evaluated per test. Each frequency can be evaluated for 1-100 seconds. In addition, two tests can be run per individual (e.g. left and right hand).

The minimum and maximum acceleration levels used in the test are tester specified between 80 and 160 dB. For frequencies less than 63 Hz, the actual maximum acceleration level for the unit is less (Figure 3). The initial start level and level rate are also tester specified. The level rate can vary between 0.1-10 dB/sec. A pause between 0.1 and 10 seconds can also be inserted in between each frequency tested. Finally, the mode of the hand switch (Bekesy or Inverse), use of cueing tone at the end of each frequency, and random white noise in the headphones are all tester selectable.

The Bruel and Kjaer vibrometer comes with the following default settings:

a) Both hands tested together; b) Minimum acceleration level: 80 dB; c) Maximum acceleration level: 160 dB; d) Start level: 120 dB; e) Start pause: 1.0 sec; f) Level rate: 3 dB/sec; g) Frequency test time: 30 seconds; h) Beep mode on (i.e. cue provided prior to each new frequency); i) Bekesy hand contact mode (i.e. the unit automatically begins by increasing the acceleration level); j) Frequency test order: 8, 16, 31.5, 63, 125, 250, 500 Hz. These represent the seven octave band center frequencies from 8-500 Hz.

To ensure accuracy, the system has both an input and output calibration routine. The input calibration routine consists of mounting the vibrometer's accelerometer onto a calibrated exciter (Type 4294). The exciter produces a constant vibration level of 140 dB at 160 Hz. This signal is used to check the sensitivity of the accelerometer and the electrical input channel to the data acquisition system. The input calibration was performed everytime the unit was moved to a new location.

The output calibration is performed after the input calibration. The output calibration scans through the seven octave band frequencies and checks the vibration output levels on the Vibration Exciter, using the input calibration results. An output calibration was performed immediately after the input calibration.

2. Electrogoniometry

Electrogoniometry is a technique used for the continuous measurement and storage of joint angles. In the case of this study, the joint of primary interest was the wrist. A new prototype device was beta tested (DataGlove, Greenleaf Medical) as part of this study. The DataGlove system consists of a recording glove, portable data logger, and Macintosh controlling software (Figure 4).

The DataGlove consists of a reusable fingerless liner, wrist deviation sensors, and a reusable sensor mounting glove. The liner is the first item placed on the hand. The fingerless liner serves both to protect the sensor mounting glove and to potentially reduce sensor crosstalk from pronation/supination of the wrist. This type of crosstalk occurs when the sensors are mounted directly on the skin. When the hand is pronated/supinated, the skin moves relative to the underlying bones and musculature. This, in turn, can lead to gross errors in goniometric measurements. When the sensors are mounted in a glove with a low coefficient of friction interface (i.e. the inner liner), the effect is minimized.

Two wrist deviation sensors are included in the DataGlove system. Each of the sensors is a series of strain gauges designed to convert wrist deviations into electrical voltages. One sensor is used to measure flexion/extension (FE) while the other is used to measure radial/ulnar (RU) deviations.

The sensors are mounted along two non-orthogonal, non-intersecting axes contained in the sensor mounting glove (Figure 5). This sensor mounting takes advantage of the biomechanical model of the wrist presented by Moore et.al. (1994). According to Moore et. al., two non-orthogonal, non-intersecting axes can be used to describe the full range of FE and RU motions in healthy human wrists. This also has the added benefit of minimizing crosstalk between the FE and the RU sensor channels. Reduction of crosstalk is achieved by fine tuning the goniometer orientation through use of specially designed calibration fixtures.

Data generated by the glove sensors is recorded using a portable data recorder. The data recorder can be worn unsupervised on the waist of the subject. A tester selectable sampling rate from 2-200 Hz is available. The recorder has a built in memory capacity of 256K. The recorder memory capacity can store eight hours of data when sampling at two Hz. A built in event marker allows the subject to identify specific tasks during the day (e.g. lunch, tasks involving different types of tools, etc.). The data recorder also has a graphical display of current FE and RU positions. However, only relative wrist positions are displayed. The prototype data recorder does not have the capability to display absolute wrist deviations.

All data collected by the DataGlove can ultimately be displayed and analyzed using the manufacturer provided software. The software displays both FE and RU deviation for the entire period sampling. A windowing feature allows the tester to examine subsets of the complete data set. Automatic calculations of percentage of time spent in FE and RU is displayed in addition to the number of zero threshold crossings. A zero threshold crossing is defined as each time the wrist crosses over the neutral axis. Finally, a portion or all of the data can be exported in ASCII text-file format for input to other software programs (such as spreadsheets, statistical analysis programs, etc.).

Calibration of the unit is required for each subject prior to testing. Calibration consists of crosstalk reduction and evaluation of range of motion. Crosstalk reduction begins by placing the subject's wrist into a specially designed calibration jig which only allow FE wrist deviation. The subject is directed to perform a full range of FE motions. While performing these motions, graphic FE and RU displays are monitored on the data recordin If crosstalk is present, it will manifest itself as false readings on the RU channel. The crosstalk is reduced by mechanically aligning the sensors with the actual wrist axes of rotation for the individual. A similar procedure for FE crosstalk is accomplished using a calibration fixture which limits the individual to only RU deviations.

The voltages produced by the sensors must also be calibrated to the range of motion for each individual. This calibration is accomplished by taking a series of manual goniometer measurements of the individual at five specific positions (extreme flexion, extreme extension, extreme ulnar deviation, extreme radial deviation, and neutral posture) while wearing the data glove. The deviations used are manually entered into the software prior to calibration. From this data, a series of two-point linear interpolations are calculated using the extreme postures and the neutral position (Figure 6). These calibration curves are used for subsequent conversion of measured voltages to degree wrist deviation.

The sensor data glove and inner lining currently come in three sizes (small, medium, large). The sensors are designed to be interchangeable with all sizes of gloves. Both glove and inner lining are reusable and can be machine washed, when required.

B. Early Vibrometry Studies

Crosshift vibrometry is defined as the difference in vibrotactile thresholds between morning and afternoon. The first crosshift vibrometry studies were conducted at McClellan AFB during the winter months (December-February 1993). Workers in various industrial shops were measured at the beginning of the workday and at the end. The purpose of the early studies was to explore the feasibility of field vibrometry testing and identify any unique problems that may be encountered in this environment. As these were the first tests using the unit, the default protocol provided by the manufacturer was used. This included placing the vibrometer test tip and armholder on the same table.

Skin temperatures were first measured at the base of the palm (above the carpal tunnel) using an infrared skin thermometer (Exergen Corp.) prior to the test. This skin temperature site was chosen based on previous clinical work using nerve conduction velocities. These studies showed that normal nerve conduction velocities through the median nerve are maintained when skin temperature above the carpal tunnel is 31°C or higher. When required, a heating pad was used to warm the skin to at least 31°C prior to initial testing.

The results of initial tests pointed out three deficiencies in the manufacturer's protocol. First, the test period (approx. 20 minutes) was much too long for crosshift vibrometry assessment over large groups of subjects. Second, some subjects perceived vibration being transmitted through the table. Third, there were large individual differences both in the mean crosshift vibrotactile sensitivity and the standard deviation of the measurement. The Bruel and Kjaer instruction manual stated standard deviation differences were the result (or combination) of varied individual response time to the vibration stimuli, subject mental status during the test (i.e. they may be getting tired), and misunderstanding of the testing protocol. However, no additional information or references were provided to support the claim.

In response to these observations, the protocol was modified. Separate test tables were provided for the mechanical shaker and armrest. To reduce sampling time, the number of test frequencies was reduced from seven to three (31.5, 250, 500 Hz). The three frequencies chosen still tested both mechanoreceptor systems while maintaining the most sensitive identification frequencies for CTS patients. Testing was also limited to the dominant hand for each subject.

During a single test, each frequency was now tested twice in a semi-random fashion (250, 31.5, 500, 31.5, 500, 250 Hz). By including repetitions at each frequency, an estimate of the precision of each vibrotactile threshold measurement could be made. To keep overall testing times short, the frequency test time was reduced from 30 to 15 seconds. To further increase the validity of each measurement, the subject was retested at each frequency until two consecutive average vibrotactile measurements were within 3 dB of each other.

The modified protocol was tested at the aircraft washrack, commissary, and B-52 spoiler shops . The commissary and B-52 Spoiler shop are described fully later in this paper. In short, the commissary is the military version of a supermarket while the B-52 Spoiler shop performs aircraft sheetmetal repair. The aircraft washrack shop personnel clean aircraft using both high pressure water (1500 PSI) and media blasting. During testing, most of the work in aircraft washrack was conducted outside and in unheated hangers.

By testing people in varied working and environmental conditions, the effect of temperature on vibration sensitivity became more evident. It was observed that some healthy people (i.e. no signs or symptoms of CTS) with warm skin temperatures at the palm would still have vibrograms indicative of vibration sensitivity loss at the higher frequencies (250 and 500 Hz). When fingertip skin temperatures of these subjects were taken, it was found that the difference between the palm and fingertip could be large. For example, the following readings were recorded from subjects during routine testing:

Palm Temperature(° C)	Fingertip Temperature(° C)
30.2	23.0
31.6	22.5
31.7	27.1
26.5	18.4
26.0	19.4

To account for the large potential temperature differences, both fingertip and palm temperatures were recorded for the three shops. Previous studies involving vibrometry generally did not report the skin temperatures even though a few studies have shown significant temperature effects for vibration sensitivity testing (Harada and Griffin, 1991, Halonen, 1986, Verillo and Bolanowski, 1986). Previous studies examining skin temperature generally agree that temperature effects are greatest at higher frequencies (>100 Hz). However, these studies differed in a) equipment used, b) anatomical site of testing, and c) vibration sensitivity testing methodology (methods of limits versus forced choice). These studies also had small sample sizes (N=8 or less) and were not specifically designed to establish minimum fingertip skin temperature recommendations.

Despite the shortcomings of these previous studies, Lundstrom et. al. (1992) used the Verillo and Bolanowski (1986) results to recommend a minimum fingertip skin temperature guideline of 28° C. On the other hand, Gerr and Letz (1993) used the same study to recommend a minimum fingertip skin temperature of 20° C. Thus, no uniform temperature guidelines currently exist. Therefore, a study was conducted specifically to evaluate the effect of fingertip skin temperature on vibrometry scores and identify a minimum fingertip skin temperature for use during typical carpal tunnel screening procedures.

C. Vibrometry and Temperature Effects

1. Methods

Twenty actively working subjects (11 male, 9 female; age 29-52, mean 33.7) without evidence of CTS by history participated in the experiment. The glaborous skin on the right middle fingertip was used for each subject. Four vibratory frequencies (31.5, 125, 250, 500 Hz) were tested on each subject in a randomized order. Six temperature classes were used in this study (17-20, 20-23, 23-26, 26-29, 29-32, 32-35° C).

Vibration sensitivity was evaluated using the Bruel & Kjaer vibrometer (model 9627). For each test, the subject placed his/her arm on the manufacturer provided armrest. The armrest was adjusted until the subject's middle fingertip was lightly resting on the five mm^2 test tip. The arm was in a pronated position. Separate tables were provided for the vibrometer and the armrest. Subjects wore headphones to minimize environmental noise and kept their eyes closed throughout the test.

The subject was instructed to push and hold a handswitch once he/she felt vibration in the fingertip and release it when they stopped feeling it. The vibration intensity level began at 80 dB (reference 10^{-6} m/sec^2) and initially increased by 10 dB/sec. Pushing the button caused the vibration to decrease by 10 dB/sec. The procedure generated a "sawtooth" pattern representing a series of vibration perception thresholds (VPTs) and vibration disappearance thresholds (VDTs) for each subject. The vibrotactile threshold was defined as the average of the VPTs and VDTs. Each test lasted 12 seconds.

Skin temperature of the test site was measured before and after each vibration sensitivity measurement using a handheld infrared surface thermometer with a stated accuracy of ±.1° C. The average of the two temperatures was used for classification purposes. The initial vibratory sensitivity measurement was conducted at ambient room temperature. The subject then placed his/her finger and hand into ice water until the fingertip temperature was between 17-20° C. Immediately upon removal from the ice water, the subject dried his/her hand and was retested for vibration sensitivity. As the hand warmed, vibration sensitivity readings were taken at each of the higher temperature classifications. In some cases, the hand needed to be artificially warmed to reach the 32-35° C category.

To test the effect of temperature on vibration sensitivity, a two-way ANOVA was conducted for each frequency tested. Temperature classification and subject were the independent variables and average vibrotactile threshold as the dependent variable. The null hypothesis stated was: there is no difference in average vibrotactile thresholds as a function of temperature classification. Post-hoc analysis of the temperature classifications were conducted using Bonferroni's inequality under the a-priori assumption that average vibrotactile thresholds for the 32-35° C temperature category were different than each of the other temperature classifications.

2. Results

Figure 7 shows the average vibrotactile threshold as a function of temperature for the four frequencies tested in this experiment. Temperature classification was a significant independent variable for all four frequencies ($p<.001$). The ANOVA R^2 values ranged from .84 to .88. Post hoc testing showed vibration sensitivity varied with fingertip temperature and, furthermore, this relationship was a function of frequency. Temperature had minimal effect at 31.5 and 125 Hz with the first statistically significant change occurring below 23°C (-2.71 dB @31.5 Hz, $p=.004$; -7.57 dB @125 Hz, $p<.001$). For 250 Hz, this temperature was below 26°C (-7.74 dB, $p<.001$). Finally, the temperature required for statistically significant changes for 500 Hz was below 29°C (-5.94 dB, $p<.001$).

3. Discussion and Conclusion

Patients with early signs of CTS may have decreased vibrotactile sensitivity in the higher frequencies (250 and 500 Hz). This experiment has shown vibrotactile sensitivity levels at these frequencies are highly susceptible to temperature effects. Since fingertip skin temperatures in the workplace can range from 21° C to 35° C, skin temperatures should be measured and controlled prior to any vibration sensitivity measurement. Failure to account for fingertip temperature effects can result in erroneous interpretations of the vibrogram information. To minimize the effect of temperature on vibratory threshold measurements, skin temperature should be kept above 29° C for all subjects. This recommendation is in line with those of Lundstrom et. al. The 20° C limit suggested by

Gerr and Letz is not applicable for higher frequencies and is low even when lower frequencies (<125 Hz) are used exclusively.

D. Additional Vibrotactile Measurement Concerns

1. Testing time

Overall testing time for some individuals was long (sometimes greater than 30 minutes) due to prolonged hand warming time in the beginning and difficulty in achieving a less than 3 dB difference per frequency. The decreased sampling time per frequency also had an unexpected effect for individuals with a large difference between their VPT and VDT.

For these individuals, the short sampling window coupled with a slow level rate change (three dB/sec) meant they could not achieve a valid measurement. That is, at least one VPT and VDT per trial could not be measured on these individuals at a particular frequency. To solve these potential problems, the level rate change was increased from 3 dB/sec to 10 dB/sec. The increased sampling rate also decreased the likelihood of the subject developing a stereotypical response pattern independent of their VPT and VDT response.

2. Learning Effect

A learning effect may be present within vibrotactile threshold measurements (Grunert et. al.,1990). The ability to calculate test-retest correlations or other statistical tests for each trial (e.g. paired t-tests, repeated measures ANOVA) would provide evidence if this was occurring in this investigation. By forcing a minimum 3 dB difference between trials, a test-retest correlation could not be effectively performed. Therefore, the minimum 3 dB difference criteria was dropped from this investigation. In its place, each frequency was measured three times per test.

3. Reliability of Vibration Threshold Measurements at Higher Frequencies

Using transcutaneously implanted tungsten electrodes, Roll et. al. (1989) demonstrated a one-to-one correspondence between some muscle spindle primary endings (Ia fibers) and vibrations up to 180 Hz. Furthermore, the study indicated most of the receptors fired harmonically with the vibration up to 80 Hz and then discharged in a subharmonic manner (1/2-1/3) with increasing vibration frequencies. The results potentially indicate that the information from the 250 and 500 Hz frequencies during vibrotactile measurements of the fingertip may be inconsistent due to misfiring of the mechanoreceptors. For this reason, 125 Hz was added to each test.

The 125 Hz frequency still measures responses from the pacinian corpuscle system. Its frequency is also low enough to ensure a one-to-one correspondence between the vibration frequency and the neural input. In addition, the 125 Hz frequency is close to the 120 Hz frequency used in a competing device (Vibratron II).

4. Initial Starting Level

Other studies have suggested a difference in VPT and VDTs depending on the starting vibration level. Individuals who start vibration sensitivity testing above their threshold level tend to have higher VPTs and VDTs than individuals who begin testing at or below their threshold level. Thus, average vibrotactile thresholds may be linked to the initial starting level.

To remove this potential confounder, the starting level was changed from 120 dB to 80 dB for each frequency. This ensured virtually all subjects would start the test at a vibration level less than their own VPT. Initial testing indicated the new starting level worked well with most subjects.

However, during testing, some subjects vibrotactile threshold would remain fixed at the 80 dB level. That is, they would constantly push the handswitch throughout the test. When questioned about their behavior, they stated they could feel even the small amount of vibration present at 80 Hz. Many explained the vibration as a circular sensation on their finger.

To see if this hypersensitivity continued for a different starting level, the test was repeated with the subject instructed <u>not</u> to push the handswitch until directed by the tester. The tester would allow the Vibrometer to automatically increase the vibration level until a point below the estimated subject's VPT. Then the tester would tell the subject to push the handswitch and resume the test as the normal.

This procedure eliminated the vibrotactile threshold hypersensitivity in virtually all subjects and produced a valid vibrotactile threshold for the frequency being the tested. The procedure was also reproducible over the three trials tested per frequency. If hypersensitivity was being exhibited by the subject, the trial would be repeated using the alternative protocol.

With all of the above changes, the length of the protocol increased. To reduce the protocol time back to manageable levels and reduce the chance of subject fatigue, the test time per frequency was further reduced from 15 to 12 seconds. Depending on the subject's initial fingertip temperature and vibrotactile threshold hypersensitivity, an average test using the final protocol lasted from five to 20 minutes with the majority of people taking 10 minutes. This meant four to six people could be comfortably tested per day.

IV. STATEMENT OF PROBLEM

Currently, an ergonomist is limited in his/her ability to quantify cumulative physical stress of the hand/wrist that may lead to CTDs in the workplace. Most of the current exposure assessment tools include checklist observational methods, videotaping, employee interviews, and other posture recording systems. These methodologies are subjective and heavily dependent on the expertise, time, bias, and interest of the ergonomist. This paper explores the use of the worker's fingertip vibration sensitivity as an exposure assessment tool in industry. That is, the worker is the exposure tool (source of ergonomic stress) and vibrometry is the biomarker for ergonomics stress. Two questions are posed related to the usefulness of this device as a biomarker for ergonomic stress:

1. Can short-term exposure to jobs with different levels of hand activities cause consistent job specific temporary changes in vibratory sensory threshold levels in workers?

INDEPENDENT VARIABLE	DEPENDENT VARIABLE
Shop Name	Crosshift Vibrometry Scores
Day Tested	

2. Are specific cumulative wrist postures (extension, flexion, ulnar deviation, and radial deviation) and wrist motions (dynamic and static) related to short-term changes in worker vibratory threshold levels?

INDEPENDENT VARIABLE	DEPENDENT VARIABLE
Wrist Postures	Crosshfit Vibrometry Scores
Wrist Motions	

POTENTIAL COVARIATES FOR BOTH RESEARCH QUESTIONS: Fingertip Skin Temperature (each measurement and changes over a shift), Sex, Age, Hand/Wrist Pain, Exposure Duration, Vibration, Test Order

V. METHODS AND MATERIALS (GENERAL)

A. Study Design

Three studies (One Day study, Two Day study, and Vibrometry and Goniometry study) were used to answer the research questions. All studies were based on observational data. The One Day study was used to identify significant sources of crosshift vibrometry variance independent of shop effects. The One Day study used data collected from the Two Day studies and previously described Preliminary studies. The results of the One Day study were used to identify specific covariates (from the list of potential covariates) for Two Day and Vibrometry and Goniometry studies analysis.

The Two Day study was a two factor (shop name, day tested) experiment with repeated measures on day tested. The Two Day study was used to answer research question one.

The Vibrometry and Goniometry study was a pilot crossectional study using an electrogoniometer to continuously monitor and record wrist postures during the work day. The Vibrometry and Goniometry study was used to answer research question two.

Subject participation in all studies was voluntary. All subjects were required to fill out an informed consent statement prior to participating. The informed consent statement was reviewed and approved by both the United States Air Force (USAF) and UC Berkeley Human Use Committees (UC Berkeley Human Use Committee Approval 93-12-46, USAF Clinical Investigation Protocol SGO 92-110).

B. General Workplace Description

All subjects were employees working at McClellan Air Force Base (AFB). McClellan AFB is a large industrial facility located in Sacramento, CA. McClellan AFB employs approximately 14,000 individuals. The major work consists of depot level maintenance of military aircraft (KC-135, A-10, F-111). Depot level maintenance consists of major repairs and system upgrades to the various aircraft and subsystems. A wide variety of skilled craftsmen including sheetmetal mechanics, electricians, and pneudraulic specialists are employed at the base. In addition, many other non-aircraft related job skills are utilized at the base (e.g. procurement specialists, administrative personnel, grocery checkout clerks, etc.). Most of the work is organized into job shops consisting of 15-25 workers. Work schedules vary throughout the base. Some people work the normal 8-hour day (40-hour week), while others work 9-hour days with every other Friday off. Most daytime shifts start at 0600 to avoid the late afternoon heat common in Sacramento, CA.

In general, each shift includes two 10 minute breaks and 30 minutes for lunch. Additional bathroom breaks are taken by workers as required. Depending on the tasks involved, up to three shifts (day, swing, graveyard) may be used in the shops. The workers are union organized mainly through the American Federation of Governmental Employees (AFGE).

Workload in the shops can be very cyclic. At times, workers may be doing hand intensive work (i.e. riveting, hand assembling, drilling, etc.) non-stop throughout the day or week. On other days, workload will slack and less hand intensive work will be used. The type and level of work being performed in the shop can vary from person to person. The location of work may vary between and within shops. Some personnel perform their work exclusively on workstations, while others perform most of their work directly on the aircraft. Some of the workload can be tied to world events, so workload predictions are difficult.

Each worker is provided specific handtools to perform his/her tasks. These tools are usually stored in a employer provided tool cart. Employees are highly discouraged from bringing tools from home to work on military aircraft. This is due to the liability and tight specifications associated with military aircraft repair and associated equipment.

C. Statistical Analysis

Data was analyzed using a combination of linear regression, Pearson product-moment correlations, paired t-tests, single and multi-factor (including repeated measures) ANOVAs, and linear discriminant analysis. Post hoc testing of factor level (treatment) effects was conducted using the Tukey-Kramer method of multiple comparisons. Assumption checking of normality, linearity, and equal variance were made using standardized residual plots and the Shapiro-Wilk W test for normality. Non-parametric tests were used when normality could not be assumed. Outliers were identified using studentized residual plots and Cook's distances, but only excluded if known gross measurement errors were present.

R^2 values were calculated and used to compare with nested and non-nested statistical models. Nested ANOVA and linear regression models were compared using F-test to remove procedures. Comparison among the estimated regression coefficients was conducted using path coefficients. Path coefficients allow comparison of the relative contribution of regression coefficients associated with variables measured in different units (lbs, ft, sec, etc.). The estimated path coefficient is the estimated change produced in the dependent variable divided by the estimated standard deviation of the dependent variable (Selvin, 1992). All statistical analysis was conducted using JMP (SAS Institute, Inc.).

VI. ONE DAY STUDY

The One Day study was conducted for several reasons. First, the descriptive nature of crosshift vibrometry was explored. Second, the One Day study identified significant covariates (from the list of potential covariates) for subsequent analysis in the Two Day and Vibrometry and Goniometry studies. Potential covariates included temperature, age, day of week tested, subject testing order, sex, and exposure duration. Finally, an estimate of the crosshift vibrometry score (CVS) measurement precision was made using a subset of 89 subjects from the One Day study population. This was necessary since a portion of the One Day study population used the two trial protocol described earlier in this study.

A. Methodology

The One Day study consisted of crosshift vibrometry scores (CVSs) for 121 subjects. The CVS was determined by subtracting the morning vibrotactile threshold measurement from the afternoon vibrotactile threshold measurement. This database included the various protocols described earlier (Initial Studies), current protocols (Two Day Study), and additional subjects who only had one crosshift vibrometry measurement. Data from the Two Day study was incorporated into this database by randomly choosing a single crosshift vibrometry measurement from each subject. Of the 121 subjects, thirty two were not tested at 125 Hz due to use of an older protocol.

The testing protocol was similar for all subjects. Vibration thresholds were measured in the morning and afternoon. Since union rules precluded measurements immediately before and after work, the exact time between morning and afternoon tests could not be standardized. However, the time of testing was automatically recorded by the vibrometry testing equipment. This allowed for calculation of elapsed time between tests. Subjects were tested one at a time.

First, the subject was seated comfortably with the dominant arm placed in the manufacturer provided armrest. Both left and right handed subjects could easily be accommodated by moving the various tables and components.

Next, the tester asked the subject a series of questions. The questions included a) name, b) birthday, c) occupation, d) office symbol, e) years in shop, f) prior physician diagnosis of diabetes or carpal tunnel syndrome, g) current pregnancy status (if female), and h) any subjective symptoms (pain, tingling) in the hand/wrist within the past week directly caused (in the subject's opinion) by the various work conditions. Items a-g were asked only during the initial test. Item h was asked during each test. All items were recorded into a notebook computer.

After entering the required information, the armrest and chair were adjusted until the subject's middle fingertip was slightly curled and lightly touching the test tip. Actual fingertip pressure on the test tip was not measured or controlled. All arms were placed in a pronated position during testing.

As explained earlier, the subject was instructed to keep his/her eyes closed and concentrate on the vibration throughout the test. The subject was given a handswitch to hold in the other hand. The subject was instructed to push and hold the handswitch when he/she felt the vibration and release the handswitch when the vibration ceased. To help the subject concentrate and minimize environmental noise exposure, headphones (with a random masking noise) were provided to the subject. The random masking noise paused in between frequencies as a cue to the subject.

Just prior to testing, the fingertip skin temperature was measured using the infrared skin thermometer. The temperature was taken at the site of testing. If the skin temperature was below 29° C, the subject was asked to warm his/her hands. The hand was warmed to (or above) 29° C either by placing it in warm water (if available) or with a heating pad. Once the skin was warmed, the fingertip skin temperature would be recorded and the test would continue.

In a few cases, the hand could not be completely warmed to 29° C in a reasonable amount of time (approximately 10 minutes). In this case, the fingertip skin temperature would be recorded and the vibrotactile threshold measurements made with the existing initial fingertip temperature.

When the subject performed the test for the first time, he/she was allowed to practice at 125 Hz prior to the beginning of the actual test. The investigator would check that the subject understood the instructions, no hypersensitivity existed, and the differences between VPTs and VDTs remained constant through the trial. If problems existed, the investigator would explain the instructions again until the subject performed a valid vibrotactile measurement. If no problems existed, the actual vibrotactile threshold measurements would commence immediately after the practice session. No practice sessions would be used for subsequent tests of the subject.

Immediately after the test was completed, the subject's fingertip skin temperature was taken at the same site as the beginning of the test. The average of the pre and post-skin temperatures was used for subsequent analysis.

B. Results

1. Crosshift Vibrometry as a Function of Frequency

CVSs were calculated for each frequency. In addition, a summary measure (AllDiff) was calculated for each subject by adding the crosshift vibrometry scores at each frequency. The histograms for each frequency and AllDiff are shown in Figure 8. A positive difference was indicative of increased vibrotactile sensitivity over the work shift.

For all four frequencies, the CVSs across all subjects were positive (Table 1). Mean values ranged from .1 dB (31 Hz) to 1.7 dB (500 Hz) with increasing frequencies having a higher CVS. A paired t-test was used to determine if the CVS was significantly greater than zero. For 125 ($p=.03$), 250 ($p=.01$), and 500 Hz ($p=.01$), the CVS was significantly greater than zero. No significant change was noted for 31.5 Hz ($p=.82$).

The Pearson product-moment correlations (Table 2) indicate a stronger linear relationship between CVSs at the higher frequencies (125, 250, 500 Hz) than between 31.5 Hz and the higher frequencies. The highest correlations were between 125 Hz and 250 Hz ($r=.70$, $p<.01$) and 250 and 500 Hz ($r=.61$, $p<.01$). Less correlation was found between the 31 Hz CVS and the higher frequencies ($r=.17$-$.23$). The correlation between CVSs at 31 Hz and 500 Hz was borderline significant ($r=.17$, $p=.06$). AllDiff was correlated with the higher frequency scores (.77-.88) more so than at 31 Hz ($r=.50$).

2. Vibrotactile Threshold Measurement Precision

Both intratrial and intertrial precision were assessed. Intratrial precision was measured using the standard deviations for each trial. Bruel and Kjaer defines standard deviation as the spread of the vibration disappearance thresholds (VDTs) and vibration perception threshold (VPTs) around the calculated mean threshold value. The following formula is used:

$$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(L_n - \mu)^2}$$

where N = number of VPTs and VDTs within each trial (variable per subject and trial)
L_n = each VPT or VDT (dB)
μ = mean vibrotactile threshold per trial (dB)
σ = standard deviation (dB)

As defined by Bruel and Kjaer, the standard deviation is not directly related to the dispersion of the mean vibrotactile thresholds per subject and trial. Rather, the standard deviation is an indication of the spread of VPTs and VDTs around a single mean vibrotactile threshold per subject and trial. The results are presented in Table 3 and represent the six trials per frequency per day which a subject's vibrotactile threshold was measured. Overall, the mean, median, and standard deviation across all subjects was relatively constant. However, the distribution of standard deviations was skewed.

To statistically test if the spread of VPTs and VDTs affected CVSs, one-way ANOVA models were developed with CVS as the dependent variable and average standard deviation as the independent variable. The average standard deviation was calculated from the six trial standard deviations per subject. Two treatment effects (<7dB and ≥7 dB) were used based on the overall distribution of average distributions across all subjects. The results are presented in Table 4. Average standard deviation had no significant independent effect on CVSs at all frequencies.

The intertrial precision was assessed by calculating the standard deviation associated with the three trials which made up the average vibrotactile threshold measurement used for the CVS. Table 5 presents the mean, median, and standard deviation across all subjects for each frequency and time of day (morning or afternoon). The median standard deviation across all groups was relatively constant and ranged from 2.0-3.1 dB. The mean across all frequencies and time of day is 2.4 dB. Therefore, any vibrotactile threshold measurement made by averaging three trials per frequency will have, on average, a standard deviation of ± 2.4 dB. For CVS, the standard deviation would double to ± 4.8 dB.

3. Temperature and Time Effects

Both the crosshift temperature (i.e. skin temperature (morning) - skin temperature (afternoon)) and exposure duration (time difference between vibrometry scores) were associated with the crosshift vibrometry score at the highest frequencies (Table 6). A positive crosshift temperature meant the average skin temperature was cooler in the afternoon than morning. Both crosshift temperature and time effects were frequency dependent (Figure 9).

Temperature effects alone were significant, but weakly associated with CVS, at 250 Hz (R^2=.06, p=.01) and 500 Hz (R^2=.18, p<.01). The direction of change was negative indicating that cooler afternoon skin temperatures (positive crosshift temperature) were associated with decreased vibration sensitivity. The magnitude of the effect ranged from 0.9 dB (250 Hz) to 1.4 dB (500 Hz) change in CVS per one °C temperature change.

Exposure duration (in minutes) was borderline significant (R^2=.03, p=.06) at 250 Hz, significant (R^2=.05, p=.019) at 500 Hz, and not significant at 31.5 and 125 Hz. For 250 and 500 Hz, the direction of change was positive indicating increased vibrotactile sensitivity was a function of increased time of exposure. The magnitude of the coefficient for time of exposure were roughly equal for 250 and 500 Hz. Exposure duration was weakly associated with CVS.

To further explore the relationship, a linear regression model was created using both exposure duration and temperature difference (Table 7) as the independent variables and CVSs at the various frequencies as the dependent variables. Interaction between the two independent variables (exposure duration*temperature difference) was also tested. The results of the multi-factor model closely followed the single factor models. At 31 and 125 Hz, the ANOVA models were not significant ($p=.22$ and $.20$ respectively). At 250 and 500 Hz, the ANOVA models were significant ($R^2=.11$ and $.25$, respectively, $p<.01$). The interaction term was borderline significant at 250 Hz ($p=.05$) and significant at 500 Hz ($p=.04$). When the interaction term was included in the model, no other variables in the regression model had coefficients significantly different from zero.

To also look at the independent effects of exposure duration and temperature difference, ANOVA models were constructed assuming no interaction between exposure duration and temperature difference. The ANOVA model remained statistically significant at both 250 Hz ($R^2=.08$, $p<.01$) and 500 Hz ($R^2=.22$, $p<.01$). At 250 Hz, only the temperature difference coefficient was statistically different from zero ($p<.01$). At 500 Hz, both the exposure duration ($p=.03$) and the temperature difference ($p<.01$) coefficients were statistically different from zero.

To directly compare the effects of temperature difference and exposure duration on the overall 500 Hz model, path coefficient were calculated. By converting each variable from units of degrees and minutes to standard deviation units, a direction comparison of the relative contribution of each variable to changes in CVS can be made. The path coefficient for exposure duration is 1.18. The path coefficient for temperature difference is -2.69. Temperature difference provides approximately 2.28 times more contribution to the CVS than exposure duration.

4. Sex, Subject Testing Order, and Day of Week

One-way ANOVA models were constructed for each frequency with CVS as the dependent variable. Sex, subject testing order, and day of the week tested were the independent variables (Table 8). Subject testing order was ranked by the month, day, and morning test time. Sex, testing order, and day of week had no significant independent effects on CVS at any frequency.

5. Age

Two issues were evaluated with age in this study. First, age was observed to be statistically associated with morning vibrometry scores for all frequencies tested (Table 9). Increasing age was weakly associated with decreased vibrotactile thresholds (i.e. higher vibrometry scores). R^2 values were relatively constant and ranged from .07 (31.5 Hz) to .14 (125 Hz). The linear regression age coefficients were approximately two times higher at the higher frequencies (.306-.338) than at 31.5 Hz (.157). No significant association was observed at any frequency between CVSs and age (Table 10). A comparison of the two relationships is shown in Figure 10.

VII. TWO DAY STUDY

A. Sample Size and Shop Selection (N=52)

To maximize the potential likelihood of an effect in CVS during the Two Day study, shops with a) a history of employees with carpal tunnel syndrome (CTS) and b) shops with employees performing roughly similar work activities in each work area were selected. These shops were selected through a records review of Air Force (AF) Form 190s (Occupational Illness Investigations), consultations with Military Public Health personnel, previous exposure data collected from the Bioenvironmental Engineering Office (the base industrial hygienists), and walk-through surveys.

Three shops at McClellan AFB were initially chosen for this study. The commissary (grocery store checkout cashiers), KC-135 Panel Shop (sheetmetal mechanics), and B-52 Spoiler Shop (sheetmetal mechanics) were selected for their high CTS risk as evidenced by previous worker compensation claims in these shops. Besides their CTS risk, the commissary represented a low force-high repetition shop while the KC-135 Panel and B-52 Spoiler shops represented high force-high repetition using the Silverstein et. al. (1986) criteria.

Preliminary sample size estimates for the Two Day study were developed using power functions (Netter et. al., 1990) with an assumed power ($1-\beta$) of .80 and alpha (α) equal to .05. An initial treatment effect of 10 dB and standard deviation of 10 dB was chosen based on previous studies concerning differences between CTS and non CTS patients (Tittaronda, 1993) and HAVS patients (Department of Physical Factors Trauma, 1993).

This corresponded to 21 employees per shop (63 total employees). The power calculations performed were based on one day of sampling.

A total of 33 personnel volunteered and participated in the Two Day study from the three initial shops (15 (Commissary), 13 (KC-135 Panel shop), 5 (B-52 Spoiler shop)). Some workers chose not to participate due to concerns about the testing procedures. Other workers could not complete the full protocol due to scheduling conflicts.

Two additional shops (the KC-135 Flight Control shop (sheetmetal mechanics) and Engine shop (engine mechanics)) were added later in the study. The KC-135 Flight Control shop performed similar tasks with similar tools as the KC-135 Panel shop. It was added to boost overall sample size. The Engine shop was added as a control group. The shop consisted of long-term employees with no prior history of CTS. The Engine shop is located in the same building as the KC-135 Panel and KC-135 *Flight Control* shops. With the addition of the two shops, a total of fifty two subjects (36 male, 16 female) participated in the Two Day study.

B. Shop Description

The operations of the shops used in the Two Day study are described below.

1. Commissary

The McClellan AFB commissary is a full service grocery store. The commissary serves the needs of military personnel, military retirees, and their dependents. Since commissary prices tend to be lower than regular grocery stores, use of the commissary is high. In addition, recent base closures in Northern California have increased the volume of business at the McClellan AFB commissary. Currently, the commissary is open seven days per week to meet the large customer demand.

The layout of the checkout stands at the commissary is designed to facilitate maximum flow of goods. Nineteen checkout stands are available. Instead of having customers choose which line they would like to checkout in, all customers are required to line up in a single line. When the customer reaches the front of the line, a computerized voice tells the customer which checkout stand they should go to. This type of system helps assure equal customer loading for the checkout cashiers.

The commissary uses the NCR Model 1255 checkout system. Each checkout stand is similarly designed and does not allow for much adjustability (Figure 11). All have a computerized cash register, scanner, scale, four legged stool, anti-fatigue mats, scale, display, and conveyor belts. The cash register is mounted approximately 16 inches over the scanner. The keyboard is designed with a 30 degree inclination.

The checkout procedure is similar for each customer. First, the customer gives the cashier any coupons they may have. Next, the customer places various sized and shaped items on a conveyor belt which brings the items to the checkout cashier. The checkout cashier then looks for the bar code on the item. If present the checkout cashier positions the item and slides the bar code over a horizontally mounted laser scanner. Usually, only one pass is needed. Once scanned, the item is placed on a second conveyor and bagged (by another individual) for the customer.

In cases where the bar code is absent or unreadable, the checkout cashier will manually enter the required information into the cash register. If items need to be weighed, the items will be placed on a scale and the appropriate merchandise code is manually entered into the cash register. The process continues until all items have been scanned or manually entered into the cash register. The checkout cashier then determines the subtotal and subtracts any coupons provided by the customer. Finally, the customer provides payment for the items (cash, check, or ATM) and the transaction is complete. The entire process involves both hands in a variety of rapid hand movements.

The checkout cashiers are required to sustain 32 scans per minute. This information is obtained from data within the cash register system itself. At the end of the day, information for each employee is provided concerning scan rate, number of items scanned, and cumulative time on the scanner. Employees not meeting the standard are given training to help improve their scan rate. An incentive pay system based on scan rate and dollar amount of merchandise processed was eliminated last year.

Both full time and part time employees are used. Full-time employees work standard 40 hour work weeks. Part-time employees work four 5 hour days and one 4 hour day per week. Additional part time employees are used to help augment the full time employees during busy periods (weekends, holidays, pay days, etc.). Given the assembly line nature of the job, rest breaks were taken on a much more regimented schedule than other jobs surveyed in this study. Part-time employees received one 10 minute break per shift. Fifteen people from the commissary participated in this study.

2. KC-135 Panel Shop

The KC-135 Panel Shop is set-up to perform corrosion removal and small sheet metal repair on 200 different KC-135 panels, engine cowlings, doors, and ferrings. At the time of the study, the shop employed 23 permanent employees working one daytime shift. The workers were classified as sheetmetal mechanics. Due to the high productivity of the shop, workers had considerable control of their work pace and break schedule. Overtime in this shop is relatively rare. Each individual is responsible for his own quality control. The workstations in this shop are non-adjustable.

Items for repair are sent by the Aircraft Modification Center. Once received, each specific part goes through a evaluation and inspection. This task is performed by one individual. This individual determines what needs to be done to each part, tags the item, and enters it into a computer control system.

The workleader uses this information to assign specific employees to specific tasks and the order in which they are to be accomplished. Work can be generally divided into two area: Engine Cowlings and Panels (which includes landing gear doors, spoilers).
Engine cowling repair tends to be complex and requires the talents of the experienced sheetmetal mechanics while panel repairs are simpler.

For the panels, the employee is mainly doing corrosion control, cleaning, metal priming and fastener repair/replacement. The engine cowling repairs consists of crack identification and repair through metal patching or replacement. Repairs vary dramatically depending on the condition of the part.

Repairs can consist of grinding, sanding, drilling, replacing fasteners, riveting/bucking, manufacturing parts, and metal priming and sealing. Tools used include pneumatic riveting guns, bucking bars, pneumatic wrenches, a variety of manual hand tools (wrenches, pliers, etc.), pneumatic drills, and sealant guns. Riveting and bucking tasks are usually performed by two individuals. Thirteen people from the KC-135 Panel shop participated in the study.

3. B-52 Spoiler Shop

The B-52 Spoiler shop is set-up to inspect and repair spoilers from various B-52 aircraft worldwide. At the time of this study, the shop employed four permanent and eight temporary workers working one daytime shift. The workers are classified as sheetmetal mechanics. Due to the high workload demand at the time of the study, workers were required to work 12 hour shifts (5:00 to 17:30). Each worker controlled his own work pace. The workstations at the B-52 Spoiler shop are non-adjustable. Each worker was assigned to a specific workstation, but assisted other workers as required.

The type of work performed by employees is dependent on the specific condition of each spoiler. Individual B-52 spoilers are received by base supply and delivered to the shop. Once at the shop, the spoiler is tagged for tracking. The process first begins with metal "fingers" (screws and rivets) being removed from the spoiler itself using a pneumatic drill and impact wrench. Each finger contains 10 rivets.

Once the fingers are removed, the spoiler is sent to another area for metal preparation (sandblasting). The fingers are sent separately to other areas for inspection, sandblasting, radiographic testing for cracks, plating/cleaning, and priming. After metal preparation, the spoiler is returned to the B-52 Spoiler shop and assigned to a specific sheetmetal mechanic.

The sheetmetal mechanic then begins his inspection of the spoiler. First, the top skin of the spoiler must be removed. This consists of removing screws and rivets. Approximately 18 1/4" screws, 13 3/16" screws are removed using a pneumatic screwdriver. In addition, 400-500 rivets are removed using a pneumatic drill.

Once the top skin is removed, the sheetmetal mechanic looks for cracks in the front spar. Approximately 99% of the front spars will need to be replaced. To remove the front spar, 150-200 rivets and 20 bolts must be taken off. Both pneumatic and manual hand tools are used.

In addition to replacing the spars, hinges associated with the spar need to be checked for alignment. Sometimes the bearings on the hinges may be worn and need to be replaced. This process is accomplished using a hand press.

After the new spar is put on, the sheetmetal mechanic must next decide if the backskin of the spoiler must be removed. The backskin is removed 40-50% of the time. Removal of the backskin requires an additional 400-500 rivets be drilled out.

Depending on the conditions of the skins, they may be repaired or replaced. The shop manufactures replacements in-house since each skin needs to be custom fit. The process requires tracing the old skin, cutting out a rough form, and trimming to fit. In addition, 400-500 new holes must be drilled and countersunk for each skin.

Once the new holes have been drilled and countersunk, the new skin(s) are riveted back on to the spoiler frame. For the backskin, approximately 400-500 D rivets (5/32" and 3/16") are shot. Rivets are categorized in alphabetic order with AA being the softest material and DD being the hardest. Usually, one person will rivet and another will buck for the entire task. The choice of bucking bar is dependent on the riveting location.

There is a lot of personal preference in the choice of riveting or bucking. However, it is not uncommon for one person to perform both riveting and bucking at the same time. The spoiler is shot in a vertical position using a pneumatic 4x (4" stroke hammer) riveting gun.

For the topskin, approximately 400-500 D rivets (5/32" and 3/16") are also shot. However, the spoiler is shot in a horizontal position instead of a vertical position. Also, the very constrained spaces during this task require the exclusive use of one riveter and one bucker.

Once the spoiler has been repaired, the fingers are replaced on the spoiler using B rivets and screws. The spoiler is prepared for shipment and sent to the next shop for further maintenance. Five people from the B-52 Spoiler shop participated in this study.

4.. Jet Engine Shop

The Jet Engine shop (or Engine shop) supports all aircraft at McClellan AFB including F-111, F-15, A-10, and KC-135s. A total of 17 full time jet engine mechanics work in the shop. The shop has one daytime shift. Overtime is rare in the shop. Overall, specific duties of the mechanics are a function of workload and parts availability. Mechanics have considerable freedom for controlling their work pace and break schedule. They also are responsible for the final quality control of their work.

The Jet Engine shop's workload comes as part of planned depot maintenance from the Aircraft Modification Center and rejections from the Flight Preparations Area. The process begins with engines being brought into the shop area. Each engine is brought in on a fixed height trailer. Once received, a mechanic is assigned to the engine and performs a Safety of Flight inspection. The mechanic writes down all the defects of the current and describes what needs to be fixed. The inspection requires the mechanic to move around all sides of the engine and assume a variety of awkward postures. The main tools used by the inspectors are borescopes (for compressor inspection), flashlight, and mirror.

After the inspection, a variety of maintenance tasks are performed by the mechanic. These include removal and replacement of variety of parts including generators, hydraulic pumps, thermostats, vanes, nozzles, wires, etc. The work requires a variety of tools including wrenches (open end, ratchet, and box), pliers, hammers, mallets, screwdrivers, metal files, and speed handles. The work is very hand intensive and requires the mechanics, at times, to frequently assume awkward postures.

Some mechanics also perform duties at the Jet Engine Test Cell. As its name implies, this facility is used to actually test engines and determine their performance characteristics. The Jet Engine Test Cell is located separately from the Jet Engine shop. After being transported from the Jet Engine shop, the engine is mounted on the test cell using screwdrivers, ratchets, and hammers. The mechanic will then operate the test cell using a console in a separate room. Depending on the performance results, the mechanic may be required to make adjustments to various components of the engine during the testing procedure. Nine people from the Jet Engine shop participated in this study.

5. KC-135 Flight Controls

The KC-135 Flight Control shop is set-up to perform corrosion removal and small sheet metal repair (metal patches) on 24-26 different KC-135 vertical stabilizers, horizontal stabilizers, rudders, flaps, elevators, and ailerons. The Flight Controls come in a variety of sizes and shapes. The shop employees 30 full-time sheetmetal mechanics and has one daytime shift. Workers have control over their work pace and breaks. While the majority of the work is performed in the shop, sometimes workers must perform their duties on the aircraft itself. The worker is responsible for their own quality control. Work is performed on non adjustable workstations.

The process begins with the part being brought into the workstation. Prior to being delivered, the part has been depainted and/or scuffed and sanded in another shop. Once the part has been set into a workstation, the evaluation and inspection personnel look at the part and determine the work needed on it.

The work is then assigned by the workleader to a specific worker. The work in this shop is similar in nature to the KC-135 Panel shop and the B-52 Spoiler shop and includes drilling, riveting, bucking, sanding, grinding, scraping, removing/installing bolts and screws, priming metal, and applying sealant. The tools used in this shop are similar to those in the KC-135 Panel shop and include pneumatic drills, pneumatic grinders/sanders, pneumatic riveting guns, bucking bars, pneumatic nut runners, sealant guns, and assorted hand tools (wrenches, hammers, screwdrivers, etc.).

As in the KC-135 Panel shop, there is a certain worker preference to specific types of jobs based on skill and work demands. Even so, workleaders rotate jobs to ensure workers remain proficient in all aspects of sheetmetal repair. Ten people from the KC-135 Flight Control shop participated in this study.

C. Field Testing Methodology

This protocol was designed to identify differences in crosshift vibrotactile thresholds between groups exposed to varying kind of ergonomic stress and consistencies within groups. Fifty two subjects participated in this protocol from five different shops (B-52 Spoiler, KC-135 Panel, KC-135 Flight Controls, Engine, and Commissary). The testing protocol was similar to that described in the One Day study. The subjects were tested on two separate workdays. Both days of testing were selected randomly for each worker.

The Bruel and Kjaer vibrometer was programmed with the following settings:

a) Only one hand tested (dominant hand); b) Minimum acceleration level: 80 dB; c) Maximum acceleration level: 160 dB; d) Start level: 80 dB; e) Start pause: 1.0 sec; f) Level rate: 10 dB/sec; g) Frequency test time: 12 seconds; h) Beep mode on (i.e. cue provided prior to each new frequency); i) Bekesy hand contact mode (i.e. the unit automatically begins by increasing the acceleration level); and j) Frequency test order: 125, 500, 31.5, 250, 500, 31.5, 125, 250, 250, 31.5, 125, 500 Hz.

After the second test of the day, subjects from the KC-135 Panel, KC-135 Flight Control, B-52 Spoiler, and Engine shops were required to fill out a task analysis sheet (Figure 12). The task analysis sheet generically described the tasks being performed during the day along with an estimate of the time needed to perform the task. In addition, each subject provided a list of tools used in the performance of the tasks.

For commissary personnel, a task analysis sheet was not required since the tasks were so similar between subjects. Scan rate, total number of items processed, and total time on the cash register were obtained for each subject at the end of the day from the computerized cash register system.

The testing conditions varied slightly between shops. For the KC-135 Panel, KC-135 Flight Controls, and Engine Shop, all subjects were tested in the same employee break room. For the commissary, testing was conducted in the store manager's office. Finally, testing for B-52 shop personnel was conducted in an office directly across the shop. Each test site was climatically controlled.

D. Results

Two separate types of models (single and multi-factor) were used for the Two Day study. A summary of the testing conditions and description of the 52 subjects is presented in Table 11.

1. Single Factor Models

a. Crosshift Vibrometry as a Function of Frequency

CVSs were calculated for each frequency. The histograms for each frequency and day of testing are shown in Figure 13. A positive difference was indicative of increased vibrotactile sensitivity over the work shift.

For all four frequencies, the mean CVSs for both days were positive (Table 12). Mean values ranged from 0.2 dB (31.5 Hz, Day 1) to 1.8 dB (500 Hz, Day 2) with increasing frequencies having a higher CVS. Under the assumption of a normal distribution, a paired t-test was used to determine if the CVS was significantly greater than zero for both days. The CVS was significantly greater than zero only for one condition (250 Hz, Day 2, p=.04). At 500 Hz (Day 2), the CVS was significantly greater than zero when a t-test was employed. However, the distribution was skewed right (i.e. toward decreased sensitivity in the afternoon and the assumption of normality could not be assumed (Shapiro Wilk W test for normality, p=.02). A signed ranked tests was used instead. The signed ranked test was borderline significant (p=.07).

The Pearson product-moment correlations (Table 13) indicated a stronger linear relationship between CVSs at the higher frequencies. The highest correlations were between 250 and 500 Hz (Day 1, $r=.74$, $p<.01$) and 125 and 250 Hz (Day 2, $r=.71$, $p<.01$). No significant correlation was found between the 31 Hz CVS and the higher frequencies. AllDiff was correlated with the higher frequency scores ($r=.80-.90$) more so than at 31 Hz ($r=.37-.45$).

b. Temperature and Time Effects

Absolute and crosshift fingertip skin temperatures (difference between morning and afternoon temperatures) are presented in Table 14. In general, fingertip skin temperatures for each test were kept above 29 °C recommended temperature. Crosshift temperature differences across all subjects were similar for the two days.

Linear regression models were constructed for each day and frequency with CVS as the dependent variable and crosshift temperature and exposure duration as the independent variables (Table 15). Temperature and exposure duration were weakly associated with CVS at the highest frequencies. For Day 1, crosshift temperature was associated with 250 Hz CVS ($R^2=.12$, $p=.01$) and 500 Hz ($R^2 = .28$, $p<.01$) CVSs. For Day 2, only the 500 Hz CVS was significant ($R^2=.16$, $p<.01$). For the significant models, the sign of the crosshift temperature coefficient was negative indicating warmer afternoon fingertip skin temperatures would lead to increased vibrotactile sensitivities. The CVS magnitude ranged from 1.2 dB (250 Hz, Day 1), 1.5 dB (500 Hz, Day 1), and 1.4 dB (500 Hz, Day 2) per one °C temperature change.

Exposure duration was not a significant factor for any frequency or day tested. A full factorial model developed with exposure duration and crosshift temperature did not provided any additional information than the crosshift temperature model alone. The full factorial model was significant at 250 Hz (Day 1, R^2 =.12) and 500 Hz (Day 1, R^2=.29, Day 2, R^2 =.16). Interaction terms were not significant.

c. Sex and Day of Week

One-way ANOVA models were constructed for each frequency and day with CVS as the dependent variable and sex and day of week tested as the separate independent variables (Table 16). Sex had no significant effect on CVS at any frequency. For day of week, there was no significant difference between day of week tested and crosshift vibrometry score for day one. On day two, a significant difference was observed at 125 Hz (R^2 =.21, p=.02). However, post-hoc analysis using Tukey Kramer HSD procedure could find no significant pairwise differences.

d. Age

A linear regression model with CVS as the dependent variable and age as the independent variable was developed (Table 17). The model was tested for all frequencies and both days of testing. No significant association was observed between age and CVS at any frequency and day of testing.

e. Shop Effect

One-way ANOVA models were constructed for each frequency and day tested with CVS as the dependent variable and shop name as the independent variables (Table 18). Shop name was significant only for one treatment condition (31.5 Hz, Day 1, R^2 =.25, p=.01). Shop name was borderline significant for 250 Hz (Day 1, R^2 =.16, p=.08).

For 31.5 Hz (Day 1), significant pairwise differences (using Tukey-Kramer HSD procedure) were observed between a) the Engine shop and KC-135 Flight Controls shop and b) the Engine shop and KC-135 Panel shop. No significant differences between shops were found for Day 2. However, at 31.5 Hz, the same overall trend between shop name and CVSs was observed on both days (Figure 14).

Engine shop personnel, on average, had increased vibrotactile sensitivity as the day progressed. The change in CVSs across all subjects in the Engine shop was larger than CVS changes in any of the other shops and across all subjects in the study. Sheetmetal shops (B-52 Spoiler, KC-135 Panel, and KC-135 Flight Controls), on average, had a slight decreased sensitivity as the day progressed. Commissary personnel, on average, had no change (< 1dB) in vibrotactile sensitivity from morning to afternoon. Given the inherent variability in vibrotactile threshold measurements, the consistent overall trend of the data from day to day was significant in themselves.

To further study these observations, the three sheetmetal shops (where work was generally similar) were merged into one group (Sheetmetal). One-way ANOVA models were constructed for each frequency and day tested with CVS as the dependent variable and shop name (three treatments instead of five) as the independent variable. For Day 1, shop name was significant for two treatment conditions (31.5 Hz, $R^2 = .24$, $p < .01$; 250 Hz, $R^2 = .12$, $p = .05$). For both frequencies, significant pairwise differences (using Tukey-Kramer HSD procedure) were observed between the Engine shop and the Sheetmetal shops. For Day 2, shop name was borderline significant for 31.5 Hz ($R^2 = .11$, $p = .06$).

f. Vibration

One-way ANOVA models were constructed for each frequency and day of testing with CVS as the dependent variable and vibration exposure (from pneumatic hand tools) as the independent variable (Figure 15, Table 19). Workers were classified into two vibration exposure levels (none, greater than one hour). This resulted in a few workers with vibration exposure less than one hour being excluded from the analysis.

Vibration exposure was associated with CVSs at only two treatment conditions. For Day 1, vibration exposure was a significant effect at 31.5 Hz (R^2 =.11, p=.02). Vibration exposed workers, on average, had decreased vibration sensitivities at 31.5 Hz over the day compared to workers not exposed to vibration (mean CVS (vibration exposed) = -1.5 dB, mean CVS (non-vibration exposed) = 1.5 dB).

For Day 2, vibration exposure was a significant effect at 250 Hz (R^2 =.08, p=.05). Both vibration and non-vibration exposed workers, on average, had increased vibration sensitivities over the day. However, non-vibration exposed workers, on average, had a significantly higher increase in vibration sensitivity over the day (mean CVS (vibration exposed) = 0.2 dB, mean CVS (non-vibration exposed) = 3.7 dB).

g. Hand/Wrist Pain

One-way ANOVA models were constructed for each frequency and day of testing with CVS as the dependent variable and hand/wrist pain associated with the job within one week of testing as the independent variable (Table 20). Hand/wrist pain was not associated with CVSs at any frequency or day tested.

2. Multi-Factor Models

a. Single Vibrotactile Threshold Measurements as the Dependent Variable

To assess potential learning and other time-related effects in vibrotactile threshold measurements, nested multi-factor ANOVA models (with repeated measures on test order) were developed for each frequency. Vibrotactile threshold measurement was selected as the dependent variable (not CVS) and subject, test order (Day 1 morning, Day 1 afternoon, Day 2 morning, Day 2 afternoon), and skin temperature were selected as the independent variables. Skin temperature was considered to be a random covariate nested within test order. The resulting plots and ANOVA tables for the four frequencies are presented in Figure 16 and Table 21. Skin temperature was a significant effect at 250 and 500 Hz ($p<.01$) as observed in the single factor model.

Mean and median vibrotactile threshold measurements per test order and frequency are presented in Table 22. For all four frequencies, a consistent pattern was observed between vibrotactile threshold measurements and time. Increased vibration sensitivity was observed across all subjects from morning to afternoon on both days of testing. However, vibration sensitivity did not continually increase from test to test. Vibration sensitivity across all subjects and frequencies on the morning of Day 2 was lower than the vibration sensitivity on the afternoon of Day 1. Significant test order effects were observed at 250 Hz ($p<.01$) and 125 Hz ($p=.05$).

The presence of a learning effect was formally evaluated by conducting a pairwise comparison test (t-test) between morning vibrotactile threshold measurements on Day 1 and Day 2 for 125 Hz and 250 Hz. Again, these were the only frequencies with significant test order effects. No significant difference between pairs was found for either frequency ($p=.58$ and $.14$, respectively). Therefore, no learning effect was present in this study.

b. CVS as the Dependent Variable (All Groups)

The consistency of CVS effects from day to day was formally evaluated using Pearson product-moment correlations and nested multi-factor ANOVA models. The Pearson product-moment correlations for CVS are presented in Table 23. CVS was observed to be significantly associated across days tested for 250 Hz ($r=.40$, $p<.01$) and 500 Hz ($r=.29$, $p=.04$).

To assess if CVS consistency from day to day was shop specific, ANACOVA and nested multi-factor ANOVA models (with repeated measures on day tested) were developed for each frequency. In the ANACOVA model, Day 2 CVS was selected as the dependent variable and Day 1 CVS, crosshift fingertip temperature, shop name were selected as the independent variables. The resulting plots (with crosshift temperature effects) and ANACOVA tables for the four frequencies are presented in Figure 17 and Table 24.

The ANACOVA model was significant at 31.5 Hz ($R^2=.42$, $p<.01$) and borderline significant at 250 Hz ($R^2=.33$, $p<.06$). For 31.5 Hz, interaction between shop name and Day 1 CVS was significant ($p=.02$). No significant independent shop name effects were observed. Crosshift fingertip temperature effects were observed at 31.5 Hz ($p=.02$).

For the multi-factor ANOVA model, CVS was selected as the dependent variable and subject (nested within shop), crosshift fingertip temperature (covariate), and shop name, were selected as the independent variables. The resulting plots (without crosshift temperature effects) and ANOVA tables for the four frequencies are presented in Figure 18 and Table 25. Subject effect was significant at 250 Hz ($p<.01$) and 500 Hz ($p=.01$).

Shop and crosshift fingertip temperature effects were similar to the single factor models. Shop effect was only significant at 31.5 Hz ($p<.01$). Crosshift fingertip temperature effects were only significant at 500 Hz ($p<.01$). CVSs across all subjects were not significantly different from day to day. No significant interaction between day tested and shop name was observed.

c. CVS as the Dependent Variable (Commissary) (N=15, Two Days)

The commissary was the only shop in this study with consistent assembly line type tasks from day to day. Linear regression models were developed to assess the relationship between CVSs and individual productivity measures (total time on scanner, items scanned, and daily scan rate) monitored for each individual. The two days of testing were considered separately (Table 26). Crosshift temperature was also included in the model.

Statistically significant relationships were seen at 125 Hz (Day 2, $R^2=.66$, $p=.02$) and 250 Hz (Day 2, $R^2=.60$, $p=.04$). Although these models were significant, not all the coefficients that made up the model were significantly different from zero. For 125 Hz (Day 2), only number items scanned ($p=.01$) and daily scan rate ($p<.01$) were significant. For 250 Hz (Day 2), only number of items scanned ($p=.03$) was significant. The sign of items scanned was positive in both cases indicating increased number of items scanned led to increased vibrotactile sensitivity. The sign of daily scan rate was negative indicating increased scan rate led to decreased vibrotactile sensitivity.

To further look at day to day variations, repeated measures ANOVAs were developed with CVSs as the dependent variable and total time on scanner, daily scan rate, items scanned, subject, crosshift temperature, and day tested as the independent variables (Table 27). Even though ANOVA R^2 values were large (.44-.75), no significant relationship between CVSs and the various factors was observed. This could be related to small sample size.

VIII. DISCUSSION (ONE AND TWO DAY STUDIES)

The results of the One and Two Day studies indicated that industrial workers in this setting, on average, had higher vibration sensitivities in the afternoon than morning. Increased worker vibrotactile sensitivity from morning to afternoon was an unexpected finding. Gelberman et. al. (1983) demonstrated that direct compression of the carpal tunnel in normal subjects and those with CTS led to decreased vibrotactile sensitivity after a period of time. The assumption at the beginning of this study was that crosshift vibrometry changes might mimic long term changes to median nerve function in a similar way temporary threshold changes are seen in audiometry, that is, they would decrease across the shift with increased compression of the nerve.

CVSs between the four frequencies tested were not equally correlated. Higher correlations were observed among the three higher frequencies (125, 250, and 500 Hz) than the lowest frequency tested (31.5 Hz). This was anticipated since the Pacinian (frequency response 50-300 Hz) corpuscle and Meissner (frequency response 5-50 Hz) corpuscle mechanoreceptor systems have different types of end receptors and may be reacting differently to environmental (including ergonomic) factors in the workplace.

CVS changes across all subjects were small for both the One and Two Day studies (0.1-1.7 dB). The standard deviations associated with the CVSs was high for both studies (4.7-6.9 dB). The small treatment effect and large standard deviations associated with this type of measurement mean the power to detect statistically significant CVS changes will be low for small sample sizes. As demonstrated by the LSN values in Table 1 and assuming similar treatment effects and group standard deviations, a minimum of 51 subjects will be needed to detect any change in CVSs at the higher frequencies (125, 250, and 500 Hz). For 31.5 Hz, a prohibitively large sample size will be needed.

Measurement error was present, but was assumed to be random and therefore was not controlled in this study. Further, the information provided by Bruel and Kjaer was lacking for full identification of this error. According to the Bruel and Kjaer methodology, each vibrotactile threshold was calculated by taking the average of all VPTs and VDTs over a specified period of time. By using this methodology, only one average vibrotactile threshold was calculated per trial and frequency. No confidence intervals for the vibrotactile threshold measurement itself was made using this technique.

As one alternative, a vibrotactile threshold could be calculated for each VPT/VDT pair per trial and frequency. The overall average vibrotactile threshold would be the same as the Bruel and Kjaer methodology since the same data is being used. However, confidence intervals can be calculated since multiple average vibrotactile thresholds are available for each trial and frequency.

The major drawback would be loss of variability information of the individual VPT/VDT data. The spread between VDTs and VPTs is lower for subjects with fast reaction time since both testing time and rate of vibration change during the test were kept constant (Figure 19). The One Day study with two treatment categories (less than 7 dB, greater than 7 dB) demonstrated this spread did not translate into statistically significant differences in CVSs. This issue would need to be researched further with additional treatment categories or using response time as a continuous independent variable.

Bruel and Kjaer make an indirect reference to this measurement error in their manual. They state the slow reactions time may indicate three things. First, the subject may not understand the test procedures. Second, the subject may need more time to respond to vibration stimuli. Finally, the subject may be getting tired.

For the first problem, Bruel and Kjaer recommend stopping the test, reinstructing the subject and starting again. For the second problem, they recommend increasing the frequency test time and retesting. No suggestions for specific increased frequency test times are given. For the last problem, Bruel and Kjaer recommend stopping the test, speaking with the subject, and retesting.

The Bruel and Kjaer recommendations are meant to increase vibrotactile threshold measurement precision for subjects with slow responses to vibration stimuli. However, no measurement precision guidelines are ever given. It is left up to the user to establish their own. We recommend establishing maximum subject standard errors for vibrotactile measurements based on a series of VPT/VDT pairs within each frequency and trial. The standard error is calculated using the following formula and assumes independence in measurement (i.e. significant autocorrelation effects between VPT and VDT may need to be corrected in the formula):

$$SE = \frac{\sigma}{\sqrt{n}}$$

The user can increase the number of VPT/VDT pairs per test to obtain a desired SE for the measurement. For example, consider the case where a maximum SE of A dB is desired for all vibrotactile threshold measurements. After the initial 12 seconds of testing per frequency, the SE for the data set can be calculated. If the SE is less than or equal to A dB, the test for that frequency is complete and the mean can be calculated. However, if the SE is greater than A dB (indicating slow response time), the test would automatically continue and a new standard error would be calculated after each new VPT/VDT is collected. This iterative process would continue until the SE is less than or equal to A dB.

The second alternative is to standardize the number of VDTs and VPTs per trial. This would reduce potential variation from various number of VDTs and VPTs collected per subject and frequency. However, this methodology does not deal with the issue of reducing the standard error of the vibrotactile threshold measurement. By increasing the precision of each vibrotactile threshold measurement, the overall power of the statistical test is increased and the ability to detect smaller treatment differences is enhanced. The ability to increase the precision of each vibrotactile threshold is critical if CVS are ever to be used in typical small sample size industrial hygiene type applications.

Besides measurements errors within each vibrotactile measurement, variation associated with the three trials which made up the average vibrotactile threshold measurement per frequency was also present. Testing conditions were similar for all three trials. The intertrial variance was consistent and not frequency dependent. Average intertrial standard deviation ranged from 2-3 dB.

As mentioned earlier in this study, Grunert et. al. (1990) looked at the reliability issues of the vibrometer. However, their study was exploring different reliability issues. In their study, the authors looked at the correlations between average VPT and VDT response over several tests rather than correlations in average vibrotactile threshold over several tests. They also included normal and CTS symptomatic subjects in their sample population. Hands were alternated during the administering of the three trials compared to the current testing methodology which measured the same hand over multiple trials within and between tests. Even though the authors reported correlations ranging from .518 to .861 for the four frequencies tested in this study (31.5, 125. 250, 500 Hz), no direct comparison of their results to this study can be made.

The small treatment effects seen in crosshift vibrometry coupled with the large inherent variance in the measurement itself makes this tool currently suitable only for large scale epidemiological surveys which can use large sample sizes to compensate for measurement errors. Its potential suitability for early CTS diagnosis will be dependent on the choice of the cutoff point. The smaller the difference in cutoff point between normal and CTS, the greater the chance for misclassification due to measurement errors alone. Traditionally, others (Burastero et. al., 1993, Hardy et. al. 1992) have used two or three standard deviations from a normal population mean as a cutoff point for CTS. Authors should also take into account the effect of within subject variability in proper selection of a CTS cutoff point.

At the highest frequencies tested (250, 500 Hz), CVSs were correlated from Day 1 to Day 2. The correlation coefficients were not large (r=.40 and .29, respectively), but statistically significant. The correlations at these frequencies were also not shop dependent (i.e. no shop and Day 1 CVS interaction). This implies an effect different from external physical stress or fingertip temperature may be independently affecting vibrotactile thresholds through the day.

The overall pattern of vibrotactile thresholds across the two days was also interesting. Instead of the average vibrotactile threshold increasing as a function of trial (i.e. a learning effect), the results showed a pattern of increased vibrotactile sensitivity in the afternoon followed by decreased sensitivity the next morning of testing. Also, no learning effect was associated with the intratrial results and comparison between the two morning readings per subject.

Gerr et. al. (1990) measured vibrotactile thresholds of the subject's great toe on two separate days using the methods of limits procedures. The results showed an increased vibrotactile sensitivity across all subjects from Day 1 to Day 2. From the data, Gerr et. al. concluded that the difference was related to a systematic criterion shift between test sessions, perhaps related to the learning effect.

Some differences existed between the Gerr et. al. study and this study. For instance, the time of each vibrotactile threshold test was not stated in the Gerr et. al. study. Gerr et. al. measured the great toe while this study measured the third digit on the dominant hand. However, the main conclusion from this study was that increased vibrotactile sensitivity through the day were related primarily to physiological rather than psychological causes such as the learning effect..

CVSs were statistically associated with physical factors including exposure duration, vibration exposure, crosshift fingertip temperature differences, and type of work performed (shop name). These physical factors did not affect CVSs in the same way. Of the four physical factors, only crosshift temperature difference and type of work performed were consistent over the Two Day study.

Exposure duration effects were greatest at the highest frequencies measured in this study. At these frequencies, increased exposure duration was associated with increased vibrotactile sensitivity. Vibration exposure was not frequency dependent. Significant effects for vibration were observed both at highest frequency (500 Hz) and lowest frequency (31.5 Hz) measured in this study. A decreased vibrotactile sensitivity was observed in vibration exposed group compared to the non-exposed group.

A significant association between CVSs and crosshift temperature was surprising since the subject's hands were maintained above 29° C prior to conducting this test specifically to reduce this phenomena. The direction of association between crosshift temperature and

CVSs was similar to previously published data involving vibrotactile threshold measurements and skin temperature (Weitz, 1941, Green, 1977, Verillo and Bolanowiski, 1986, Klinenberg et. al., 1994). Lowered skin temperatures led to decreased vibrotactile sensitivity with the effect greatest at the highest frequencies tested (250 and 500 Hz). However, this study showed the magnitude of the CVS change at the higher frequencies (approximately 1-2 dB/°C) was roughly similar to the overall CVS change across all subjects. In short, crosshift temperature is a strong confounder at the higher frequencies and must either be controlled or measured for in all CVS measurements even if the temperature is greater than 29° C.

A statistically significant shop effect was observed only at 31.5 Hz. This effect was observed in the univariate model and persisted when controlled for fingertip temperature and day tested. This suggests the Meissner corpuscle mechanoreceptor system may be sensitive to physical (including ergonomic) stressors. The unique aspect of the shop effect was that as a group, the Engine shop's personnel had increased vibrotactile sensitivity at the end of the day. The commissary had little change while the sheetmetal shops had slightly decreased sensitivity.

Engine shop personnel were long term employees (many with greater than 20 years experience) with no history of CTS. Therefore, their risk of CTS development was low. The Engine shop tasks differed from the other groups. The tasks involved low repetitions with infrequent use of high force. Primarily, manual hand tools were used. In contrast, commissary personnel performed low force, highly repetitive tasks while personnel in the sheetmetal shops performed high force, high repetitive tasks with intermittent exposure to vibration.

Defining ergonomic stress in these groups was difficult. The task analysis sheet used in this study was designed to identify shops in the force and repetition categories described by Silverstein et. al. (1986). By using the task analysis sheets, specific tasks associated with the individual could be identified and the task ergonomic stress measured or estimated.

However, these particular shops did not lend themselves to such a broad categorization. With the exception of the commissary, multiple tasks were performed by the workers in a non-assembly line fashion. The tasks varied from day to day and were not consistent from worker to worker. Therefore, one worker could be categorized as high force-high repetition and another worker in the same shop as low force-low repetition. The situation could easily change the next day both workers were tested. In this type of environment, force and repetition categorization would need to be accomplished for each worker independent of their shop affiliation.

Grip force estimation for each task was initially made using surface electromyography of the finger flexor muscles. Surface electromyography is most accurate for static and limited dynamic activities. In this study, electromyography could only be performed on limited subjects, for limited periods of time, and for a limited number of tasks. Many of these tasks had both dynamic and static components. For the commissary, EMG measurements were not considered given high velocity movements performed by the workers.

Even with static force-EMG calibration curves being developed for each subject prior to testing, variability of the measurements between and within subjects was high. Further, it was unclear how to estimate force for tasks not being measured by EMG analysis. In the end, it was felt group force estimation by EMG analysis was too error prone.

The commissary was more like an assembly line type of operation. Unlike the other four shops in this study, each worker was monitored continuously. Ergonomic exposure in this shop was measured through readily obtainable productivity measures. These included daily scan rate, daily time on scanner, and number of items scanned. It was assumed at the beginning of this study that these measurements could be used to represent task duration and repetitiveness.

Significant relationships were observed intermittently at the higher frequencies between CVSs, daily scan rate, and number of items scanned. For these relationships, daily scan rate and number of items scanned had opposite effects. Increased daily scan rate led to decreased vibrotactile sensitivity while increased number of items scanned led to increased vibrotactile sensitivity.

However, no consistent day-to-day significant associations were observed between these productivity factors and CVSs at any frequency. This may be a power issue given the relatively small sample size (15) used in this study. It may also mean additional factors related to CVSs (such as force and awkward posture) were not being measured by the productivity factors.

In summary, CVS was sensitive at all frequencies, especially higher frequencies to temperature. Exposure to vibration was related to decreased vibrotactile sensitivity. When fingertip skin temperature was controlled, a relationship between CVS and work type was only observed at 31.5 Hz. Unfortunately, the ergonomic assessment techniques used in the One and Two Day studies were unable to classify differences between work type that might explain the effects observed at 31.5 Hz.

Given the variability of tasks performed by people within the same shop, a worker specific ergonomic exposure technique was needed. Electronic goniometry using the DataGlove was selected because of its ability to continuously monitor wrist motions of workers throughout the workday.

VIBROMETRY AND GONIOMETRY STUDY

A. Sample Size

The Vibrometry and Goniometry study was a follow-on pilot study based on the results of the Two Day study. A total of 16 subjects were evaluated as part of this study. The subject population included six from the commissary, five from the KC-135 Panel shop, and five from the Engine shop. [illegible]s were randomly selected from each shop. The day tested for each worker was randomly selected.

B. Field Testing Methodology

One person per day was tested. The sequence of events began with the subject being fitted with the DataGlove (Greenleaf Medical). First, the proper size glove was chosen for the subject being tested. In general, female subjects tended to fit best in the small glove while male subject preferred the large glove. The most difficult fitting occurred on subjects with very thin wrists and those subjects with varying hand/arm anthropometry (e.g. small hands with large forearms).

After the glove was fitted to the subject, the subject was seated and the calibration procedure began. Calibration of the unit was conducted using a manual goniometer and the procedures previously discussed. Calibration of the unit could take between 5 and 15 minutes depending on the need of adjustment of the individual electrogoniometers. Care was taken to ensure the RU sensor was positioned over the radius. All calibrations were performed with the subject's arm in a pronated position.

After calibration of the unit, the subject performed a series of movements to ensure the relative accuracy of the unit. These movements were conducted standing up and included the following sequence:

a) Start fully pronated with no other deviations

b) Slowly move to extreme extension

c) Return to a

d) Slowly move to extreme flexion

e) Return to a

f) Slowly move to extreme ulnar deviation

g) Return to a

h) Slowly move to extreme radial deviation

i) Return to a

j) Slowly supinate until full supination is reached

h) Return to a

A typical plot of movements can be seen in Figure 20. The graph was compared with the input calibration data to see if they were similar. If large discrepancies were noted, the calibration would be redone. Approximate accuracy of the glove is ± 5° based on use of previously tested technology (Smutz et. al., 1994). The sampling rate for the DataGlove was set at 5 Hz.

After calibration, the subject was instructed on the proper use of the unit. The single most important instruction was the proper use of the event marker. The subject was told to push the event marker prior to going on a break (i.e. lunch, restroom, etc.) and then push the event marker just prior to returning to work. The subject was also instructed to keep a chronological log of activities performed during the day. Through this methodology, differences in hand movements between work and rest were identified and quantified.

While wearing the calibrated fingerless glove, the subject was tested on the vibrometer using the previously described protocol. Fingertip skin temperatures were taken both pre and post vibrotactile threshold testing. If the fingertip skin temperature was below 29°C, the subject would perform hand exercises (e.g. making a fist and releasing) until the skin was sufficiently warmed.

After the vibrotactile threshold measurements were taken, the recording unit was activated and the subject began performing his/her normal work tasks. These work tasks were intermittently monitored by the investigator. Near the end of the day, the subject returned to the test site and the datalogger was turned off. Prior to removing the glove, the subject performed another vibrotactile threshold measurement.

After the vibrotactile threshold measurement, the goniometer data was downloaded to a computer and a plot of the days activity was shown to the worker. By showing this data to the worker, the specific event markers could be identified and verified with their log entries. This was important since sometimes the subject would inadvertently push the button multiple times or forget to write down a break identified by the event markers.

In addition, direct viewing of the plot by the subject allowed the investigator to get a qualitative feeling about the relative accuracy of the data. This was accomplished by discussing the individual tasks with the subject (name of task, tools used, position of work) and comparing the subject's verbal and written comments with the goniometer data. The subject also appreciated the direct feedback of data from the experiment.

A variety of data reduction techniques were used for the goniometric data. First, the overall mean and standard deviations for the shift were calculated for both FE and RU deviations. Next, the data were processed using an exposure variation analysis (EVA) technique initially developed for electromyography data by Mathiasson and Winkel. (1991). The EVA technique was developed specifically for observational ergonomic studies of this type.

Under this data reduction technique, the wrist angle data was binned into different wrist deviation and continuous time categories. Seven wrist deviation categories were selected for FE deviations:

>50E, 30E-50E, 10E-30E, 10E-10F, 10F-30F. 30F-50F, >50F

Similar categories were used for RU deviations. The overall percentage of time spent in a particular wrist deviation and continuous time category was also calculated. Continuous time categories (CTC) were defined as the continuous amount of time a subject's wrist deviation remained in a particular wrist deviation category. The categories were selected from an exponential time series expansion to help differentiate dynamic and static hand movements:

0-.25, .25-.5, .5-1.0, 1.0-2.0, 2.0-4.0, 4.0-8.0, >8.0 sec $t=2^x$ where x= -2 to 4

The 0-.25 category included the quickest hand movement that can be identified at a 5 Hz sampling rate. With this method, a pictorial representation (EVA plots) of overall hand movement was made. Separate graphs were required for FE and RU. An example of the raw and transformed goniometry data is presented in Figure 21. The transformed data is a three dimensional bar chart with continuos time periods and wrist deviation as the x and y axes and percentage of working time as the z axis. The height and distribution of the bars gives an indication of the average wrist deviation, range of motion, and rapidity of movement during a given time period.

A unitless summary measure called mean continuous time (MCT) was calculated from the data. Each CTC was numbered sequentially from 1 to 7 (where 1= 0-0.25 sec and 7= >8.0 sec). MCT was the weighted average of %Working Time (%WT) spent in each continuous time category over the time of data sampling:

$$MCT = {}_{i}\sum CTC_i * \%WT_i$$

A few isolated problems occurred during data collection. In one case, the subject's cord linking the DataGlove to the datalogger became tangled and affected the recording goniometers. In another instance, the subject did not completely understand the directions and disconnected the glove from the datalogger during breaks. For these cases, the usable data for each subject was separated and analyzed.

C. Results

1. Elapsed Time vs Goniometric Measurements

A typical plot of FE and RU angles over a day is presented in Figure 22. The vertical lines are timing marks indicating a change in task or break. Table 28 shows the elapsed time between vibrotactile threshold measurements, total individual goniometer time, and an estimate of break time within the measurement period. The estimate of break time was calculated by adding up the subject recorded individual break periods during the day.

Elapsed time between morning and afternoon vibrotactile threshold measurements ranged from 174 to 378 minutes (mean = 319 minutes, σ = 56 minutes). The goniometer time ranged from 105 to 354 minutes (mean = 280 minutes, σ = 74 minutes). On average, the goniometer recorded wrist activity for 87% (range 49-97%) of the time between vibrotactile threshold measurements. Two individuals had less than 61% of their total wrist activity recorded. As explained earlier, this was due to mechanical breakdown during testing (49%) and misinterpretation of instructions (i.e. removing data cables during breaks, 60%) (Figure 23).

2. DataGlove Measurement Accuracy

An assessment of the DataGlove measurement accuracy was made with one subject. Calibration curves were developed for RU deviations over various degrees of pronation and supination (0, 30, 60, 90 degrees pronation). FE deviation was evaluated only at 90 degrees pronation. Ninety degrees of pronation corresponded to the conditions used to field calibrate the DataGlove.

The calibration curves measured the relationship between wrist joint angles using a manual goniometer and the DataGlove. Linear regression models were developed over the entire range of motion. The manual goniometer readings was the independent variable. The DataGlove output was the dependent variable. The DataGlove provides raw signal output in bits. Crosstalk effects were also evaluated during the calibration. Results of the linear regression is presented in Table 29.

The DataGlove provided a fairly linear response. The highest R^2 value for RU (.99) was measured in a 90° pronated position. This corresponded to the hand position during initial sensor calibration. As the wrist was supinated, the overall linearity of the unit decreased slightly with the lowest R^2 value for RU (.94) occurred when the wrist was in a 0° pronated position. A R^2 value of .98 was observed for the one FE calibration experiment conducted in this study.

Crosstalk was present to a limited extent in all measurements. An example of crosstalk is shown in Figure 24. In general, the effect of the crosstalk for RU deviations was minimal at neutral posture, rose slightly, and remained fairly constant over the range of motion. Crosstalk effectively caused the DataGlove to add flexion or radial deviation units to virtually all measurements. The crosstalk effect was minimal for wrist extensions.

3. EVA Plots

Appendix I contains EVA plots and corresponding working distributions for all subjects in the study. Both wrist FE and RU plots are included. For the initial analysis, subjects were grouped by shop and the average shop response to physical stress was qualitatively assessed. The EVA plots based on these average shop responses is presented in Figure 25.

For quantitative assessment, the shop grouping factor was removed and linear regression models developed. These linear regression models looked at individual CVSs as a function of their exposure to physical stresses. Further, linear discriminant analysis was used to statistically determine if significant shop differences between physical stress parameters exists.

Table 30 contains summary shop response data. Looking first at the wrist FE deviations, there is a stark contrast in percentage working time distribution between the commissary and subjects in the other two shops. The wrists of commissary personnel, on average, were extended greater than 10 degrees for 70% of the time and extended greater than 30 degrees for 33% of the time. Flexion greater than 10 degrees was present only 8% of the time. Their movements as a group were also very dynamic; 48% of the overall working time was spent moving from one deviation category to another in one second or less. The commissary as a group had an overall dynamic to static ratio of 4:1.

In contrast to the commissary, personnel in the Engine and KC-135 Panel shops spent most of their working day in relative static postures. For the Engine shop, only 21% of the working time was spent moving between categories in one second or less; 36% of the working time was spent in a single deviation category for more than eight seconds. The KC-135 Panel shop had similar results with 35% of the working time spent in a single deviation category for more than eight seconds and 18% in one second or less. The overall dynamic to static ratio for the Engine and KC-135 Panel shops was similar (0.6:1 and 0.5:1, respectively).

Wrist deviation patterns for these two shops also differed significantly from the commissary. While the ratio between time spent in extension (>10 degrees) and flexion (>10 degrees) was approximately 8.8:1 for the commissary. The KC-135 Panel shop and Engine shop were more balanced (3.9:1 and 1.9:1 respectively). Commissary and Engine shop personnel, on average, spent more time in extreme extension (> 30 degrees) than extreme flexion (> 30 degrees) (16.5:1 and 10.0:1, respectively). For the KC-135 Panel shop personnel, the ratio was more balanced (3.1:1). In general, all personnel in the study spent more time in extension than flexion.

Commissary personnel used quick wrist movements centered around extended positions. Engine shop personnel tended to use slower wrist movements centered around the neutral axis with exertions to extremely deviated positions. KC-135 shop personnel primarily used slow wrist movements centered around the neutral axis with less exertions to extremely deviated positions than Engine shop personnel.

RU distribution patterns followed similar trends to FE distributions. Commissary personnel were ulnar deviated greater than 10 degrees for 99% of the time and ulnar deviated greater than 30 degrees for 69% of the time. Radial deviation greater than 10 degrees was present <1% of the time. The movements were still dynamic, but less so than in FE; 28% of the overall working time was spent moving from one deviation category to another in one second or less.

Personnel in the Engine and KC-135 Panel shops spent a greater portion of the day in relative static postures for RU deviations. For the Engine shop, 46% of the working time was spent in a single deviation category for more than eight seconds. The KC-135 Panel shop had similar results with 47% of the working time spent in a single deviation category for more than eight seconds.

The ratio between time spent in ulnar deviation (>10 degrees) and radial deviation (>10 degrees) was approximately 6.9:1 for the Engine shop, 11.2:1 for the KC-135 Panel shop, and 99.0:1 for the commissary. Commissary shop personnel, on average, spent a great proportion of the working time (69%) in extreme ulnar deviation. This was much higher than either the KC-135 Panel (22%) or Engine (12%) shops. In general, the distribution of working times was similar for the KC-135 Panel and Engine shops across all subjects.

4. Summary Measures

Mean FE (MFE), mean RU (MRU), standard deviation FE (SDFE), standard deviation RU (SDRU), mean continuous time FE (MCTFE), and mean continuous time RU

(MCTRU) were calculated for each individual. A positive MFE value was defined as extension. A negative MFE value was defined as flexion. A positive MRU value was defined as ulnar deviation. A negative MRU value was defined as radial deviation. SDFE and SDRU were the sample standard deviations associated with MFE and MRU. SDFE and SDRU were related to the range of wrist postures during the sampling period.

The number of data points used for these calculations ranged from 31,494 to 106,129. An example of a typical FE and RU distribution is shown in Figure 26. No distinct bimodal peaks were noted in any subject. Biomodal peaks would be indicative of two distinct wrist positions assumed by the worker during the day (e.g. break and work).

The summary measures in Table 31 further illustrate the differences between the three shops. To statistically determine if the summary variables were shop-related, a series of one-way ANOVA models was developed. For each model, a summary variable (MFE, SDFE, etc.) was used as the dependent variable. In all cases, shop was chosen as the independent variable.

In all shops, the mean wrist postures were in extension and ulnar deviation. MFE and MRU values were highest in the commissary (19.6°, 35.6°), followed by the KC-135 Panel shop (12.3°, 17.9°), and the Engine shop (9.3°, 11.6°). No shop effect was observed for MFE (ANOVA R^2=.11, p =.45). Shop effect was significant for MRU (ANOVA R^2=.55, p <.01).

Mean SDFE values for each group ranged from 17.6-23.4. Mean SDRU values for each group ranged from 12.1-14.0. Shops effect was significant for SDFE (ANOVA R^2=.42, p=.03). No shop effect was observed for SDRU (ANOVA R^2=.06, p=.66).

ANOVA models using MCTFE and MCTRU as the dependent variables provided similar conclusions as the EVA plots. Commissary personnel tended to use quicker wrist motions than their KC-135 Panel and Engine shop counterparts. Both MCTFE (ANOVA R^2=.88, p<.01) and MCTRU (ANOVA R^2=.72, p<.01) had significant shop effects.

5. Linear Discriminant Analysis

Linear discriminant analysis is a statistical tool designed to allow an observation to be classified into several categories. It also is useful in developing understanding of the structure of multivariate data. Since many of the individual summary variables had significant independent shop effects, linear discriminant analysis was used to determine the best subset of the summary variables for prediction of shop classification. Further, the variables selected from the linear discriminant analysis were used in the linear regression models as independent variables with CVSs at various frequencies as the dependent variables.

Discriminant analysis creates a new set of variables called canonical variables. The canonical variables are linear combinations of the original variables. The canonical variables are orthogonal to each other and have coefficients designed to maximize separation between the groups. With the three treatment groups (shops) used in this study, two canonical variables can be formed.

A good discriminant analysis model can be assessed by a) plotting the canonical variables and seeing if clusters form or b) testing how good the model can predict group membership from the existing test data. The overall worth of a discriminant function is defined by Wilks' lamda (λ^2). λ^2 is the proportion of the variation in the discriminant scores not accounted for by the discriminant function (Selvin, 1992).

The first discriminant function was developed using all six summary measures. The corresponding canonical centroid plot is presented in Figure 27. From the plot, it can be seen that SDFE, MCTFE, and MRU are the variables most responsible for the separation between the groups.

The eigenvalue for the first canonical variable is 19.2 and 1.6 for the second canonical variable. This mean that the first canonical variable alone can explain 92% in the variation across all shops. The discriminant function was significant (λ^2=.02, $p<.01$). The discriminant function was 94% effective (15 out of 16 subjects) in correctly predicting group classification from existing test data.

A subset of three summary measures (SDFE, MCTFE, MRU) was an even more effective discriminant function. The discriminant function was 100% effective (16 out of 16 subjects) in correctly predicting group classification from existing test data. The corresponding canonical centroid plot is presented in Figure 28. The eigenvalue for the first canonical variable is 19.1 and 1.8 for the second canonical variable. This means the first canonical variable alone can explain 91% in the variation across all shops. The discriminant function was significant (λ^2=.03, $p<.01$).

A summary of the linear discriminant coefficients for the two models is presented in Table 32. A linear discriminant function using only SDFE and MCTFE was not as effective (94%, 15 out of 16 subjects) as the three variable model. Therefore, a model using SDFE, MCTFE, and MRU was best in classifying individuals into the correct shop.

6. Linear Regression Models

Exploratory multi-factor linear regression models were developed using TIMEMIN (exposure duration), TEMPDIFF (crosshift temperature difference), the goniometer measurement parameters (MCTRU, MCTFE, MRU, MFE, SDFE, SDRU) as independent variables, and CVSs at the four frequencies (31.5 Hz, 125 Hz, 250 Hz, 500 Hz) as dependent variables. Two types of multi-factor analyses were performed. The first multi-factor models used variables which were found to be significant independent factors. The second multi-factor models used variables from the best fit linear discriminant function. Statistically significant models were found at 31.5 Hz and 500 Hz. No significant association between the combination of factors was observed at 125 and 250 Hz.

a. 31.5 Hz

Linear regression models were developed with CVS as the dependent variable and TIMEMIN, TEMPDIFF, MCTFE, MCTRU, MFE, MRU, SDFE, and SDRU as separate independent variables (Table 33). Two distinct subset of variables were chosen for the multi-factor linear regression models: one based on the univariate analysis and one based on the linear discriminant analysis. TIMEMIN (R^2=.30, p=.03), MCTFE (R^2=.37, p=.01), MCTRU (R^2=.30, p=.03), and MRU (R^2=.31, p=.02) were significant independent factors. According to the linear regression models, increased exposure duration and relatively static movements (higher MCTFE or MCTRU) led to increased vibrotactile sensitivity in the afternoon. In contrast, higher mean ulnar deviation angles led to decreased vibrotactile sensitivity in the afternoon. TEMPDIFF, MFE, SDFE, and SDRU were not significant independent factors.

The correlation matrix for TIMEMIN, MCTFE, MCTRU, and MRU is presented in Table 34. MCTFE and MCTRU were highly correlated (r=.96, p<.01). A plot of this relationship is shown in Figure 29. TIMEMIN was not correlated with MCTFE (r=.11, p=.69) or MCTRU (r=.06, p=.81). MRU was negatively correlated with MCTFE (r=-.73, p<.01), MCTRU (r=-.66, p<.01), and TIMEMIN (r=-.50, p=.05).

Multi-factor linear regression models were developed using various combinations of TIMEMIN, MCTFE (or MCTRU), and MRU as the independent variables and CVSs as the dependent variable. The results are presented in Table 35. The full facto[illegible]del (i.e. with all possible interactions) is shown first. The next model shown is the first significant nested model. All subsequent restricted models are then shown.

The best model fit model with all coefficients significant involved the independent effects of TIMEMIN and MCTFE (R^2=.60, p<.01) (or MCTRU (R^2=.56, p<.01)). Interaction in both models was not significant (p=.38 and .39, respectively). The coefficients of these models (both raw and standardized) is presented in Table 36. In both models, the intercept and coefficients were significant (p<.01). The sign of the intercept is negative. The sign of the coefficients is positive. This means the highest vibrotactile sensitivity increases in the afternoon were associated with relatively static movements conducted over a long period of time. In the standardized model, TIMEMIN, MCTFE, and MCTRU have the same relative effect on CVS. Given the high correlation between MCTFE and MCTRU, the models are essentially interchangeable.

Multi-factor linear regression models using variables from the linear discriminant analysis were developed with various combinations of SDFE, MCTFE, and MRU as the independent variables and CVSs as the dependent variables. The initial best fit model with these variables involved a full factorial SDFE, MCTFE, and MRU model (Table 37). This model had an R^2 value of .89 (p<.01). SDFE, MCTFE, SDFE*MCTFE (i.e. pair-wise interaction), and the intercept were not significant. Interaction between all three variables (SDFE*MCTFE*MRU) was significant (p=.02).

SDFE, MCTFE, and SDFE*MCTFE were removed from the full factorial model. By removing these factors, the model and all remaining coefficients became significant (R^2=.69, p<.01). The intercept was not significant (p=.08). By removing SDFE and SDFE*MCTFE from the full factorial model, the model improved further (R^2=.81, p<.01). In this model, all coefficients (including the intercept) were significant. The intercept, SDFE*MRU, and MCTFE*MRU were negative. MRU, MCTFE, and SDFE*MCTFE*MRU were positive. SDFE (p=.09) and SDFE*MCTFE (p=.07) added no significant new information to the model. In summary, two distinct best fit models explained the differences in 31.5 Hz CVSs: one relatively complex model containing MRU, MCTFE, SDFE*MRU, MCTFE*MRU, and SDFE*MCTFE*MRU (Adjusted R^2=.72) and a simpler model containing TIMEMIN, MCTFE (or MCTRU) (Adjusted R^2=.49).

b. 500 Hz

Linear regression models were developed with CVS as the dependent variable and TIMEMIN, TEMPDIFF, MCTFE, MCTRU, MFE, MRU, SDFE, and SDRU as separate independent variables (Table 38). Two distinct subset of variables were chosen for the multi-factor linear regression models: one based on the univariate analysis and one based on the linear discriminant analysis. TIMEMIN (R^2=.22, p=.07) and MFE (R^2=.24, p=.06) were each borderline significant independent factors. TIMEMIN was not correlated with MFE (r=-.20, p=.45).

Based on the above results, multi-factor linear regression models were developed. Combinations of TIMEMIN and MFE were used as the independent variables. CVSs were the dependent variables. The results are presented in Table 39. The R^2 value for the best fit model was .57 ($p<.01$). Interaction was not significant in the model. All coefficients and the intercept were significant. The sign of the intercept was negative. The sign of TIMEMIN and MFE was positive. This means the highest vibrotactile sensitivity increases in the afternoon were associated with an extended wrist position over a long period of time. In the standardized model, TIMEMIN and MFE had the same relative effect on CVSs..

As a comparison to the 31.5 Hz linear regression models, models with TIMEMIN and MCTFE (or MCTRU) as independent variables were developed. The results are presented in Table 40. Both models were borderline significant (p= 07 for both models). Interaction was not significant in both models. However, the addition of the MCTFE (or MCTRU) did not add statistically significant information to a model containing only TIMEMIN (p=.16 and p=.15 respectively).

Multi-factor linear regression models using variables from the linear discriminant analysis were also developed with various combinations of SDFE, MCTFE, and MRU as the independent variables. CVSs were the dependent variables. The independent variables chosen from the best fit linear discriminant function.

The best fit model contained two pairs of two-way interaction (SDFE*MCTFE and SDFE*MRU). The R^2 value for this model was .64 (p=.04). The coefficients for this model are presented in Table 41. All coefficients and the intercept were significant in the model. The sign of MCTFE, SDFE, and MRU in the model was negative. The sign of the intercept and interaction terms was positive. In the standardized model, the two interaction terms exerted the greatest influence on CVSs. In summary, two distinct best fit models explained the differences in 500 Hz CVSs: one relatively complex model containing MRU, MCTFE, SDFE SDFE*MCTFE, and SDFE*MRU (Adjusted R^2=.47) and another simpler model containing TIMEMIN and MFE (Adjusted R^2=.50).

X. DISCUSSION (VIBROMETRY AND GONIOMETRY STUDY)

This study demonstrated the potential usefulness and feasibility of continuous full shift wrist motion sampling in quantifying individual wrist motions in a variety of workplaces. The results of this study indicate that CVSs were generally associated with cumulative worker wrist motions over the day. The associations were not significant for all frequencies tested. In the two frequencies with statistically significant models (31.5 Hz, 500 Hz), the exact combination and interaction of variables was not the same. However, similar general relationships were observed in both groups.

CVSs were related specifically to rapidity of movement in flexion/extension (MCTFE), range of motion in flexion/extension (SDFE), and average ulnar/radial deviation (MRU). Highly dynamic wrist movements (small MCTFE) and large ulnar deviations (large MRU) were associated with decreased vibration sensitivity. Large wrist range of motions (large SDFE) were associated with increased vibration sensitivity.

The significant models in this study not only included the independent factor effects, but also interaction between the variables. This means various combinations of dynamic wrist motions, wrist range of motion, and average wrist deviation may have a greater effect on CVSs than the individual factors alone. One possible theory is the combination of these three factors affects an individuals carpal tunnel pressure in different ways. These carpal tunnel pressure changes during the day ultimately result in vibrotactile threshold changes from morning to afternoon.

Carpal tunnel pressure in individuals has been previously shown to be related to static wrist posture (Rempel et. al., 1992). The relationship between intracarpal pressure and wrist deviation is u-shaped with large increases in intracarpal pressures occurring for extreme wrist deviations (both FE and RU). The lowest intracarpal pressures were recorded at a neutral posture. Similar results have been seen in subjects typing at different wrist postures (Rempel and Horie, 1994).

Dynamic movement also affects intracarpal pressure. In one recent study, Rempel et. al. (1994) continuously measured the carpal tunnel pressure in nineteen healthy subjects while performing a short-term (5 minute) task of loading and unloading one pound cans from a box. Wrist motions were continuously monitored using an electrogoniometer. During the task, intracarpal pressures fluctuated. Median pressure was elevated above baseline conditions. After task completion, intracarpal pressures returned almost immediately to baseline levels.

The authors concluded from the results that the pressure increase in the carpal tunnel may be great enough to reduce the flow of blood in the epineurial vessels. This could ultimately affect fiber function which could be manifested in vibrotactile threshold changes. The authors also assumed the blood flow in the epineurial vessels depended directly on the level and duration of low intracarpal pressures in the individual. They felt any anatomical factors that prevent the intracarpal pressure from returning to baseline levels for prolonged periods may ultimately lead to epineurial edema.

Even though the tasks monitored in this study were more complex, indirect associations between intracarpal pressure and the measure wrist postures can be made. For commissary personnel, workers were working with a highly dynamic task involving a wide range of wrist movements. However, the mean of all wrist postures was extreme ulnar deviation with some wrist extension. The extreme average wrist deviation would result in an elevated mean intracarpal tunnel pressure which would ultimately lead to nerve compression and decreased vibrotactile sensitivity.

On the other hand, Engine shop personnel worked mainly in a neutral posture, with relatively static wrist postures, and occasional exertions to extreme postures. On average, Engine shop personnel had increased vibrotactile sensitivity as the day progressed. This type of wrist posture would be most conducive toward maintaining near baseline intracarpal pressures during the work day. Further, occasional movement to extreme wrist postures may help stimulate extracelluar fluid movement out of the carpal tunnel and further reduce baseline intracarpal pressures. Reduced intracarpal pressures may improve vibrotactile sensitivity through increased microcirculation.

KC-135 Panel shop personnel had wrist profiles similar to Engine shop personnel. The two major differences were a reduced range of wrist motion (i.e. less extreme postures than Engine shop personnel) and potential exposure to vibration. Both reduced range of wrist motion and exposure to vibration were associated with decreased (or reduced increased) vibration sensitivity in both this study and the One and Two Day studies.

Another factor that may be responsible for vibrotactile threshold changes during the day was changes in microcirculation not only to the median nerve, but also the end receptors. Active dynamic work, in general, simultaneously increases blood flow and blood pressure to the peripherary. Overnight, extracelluar fluids within the body have redistributed to the extremities (including the hand and wrist). This potentially could increase intracarpal pressures slightly and cause decreased vibrotactile threshold in the morning. As the day passes, not only do the extracelluar fluids redistribute away from the extremities, but active hand work performed by the worker may increase the intraneural blood pressure and improve overall microcirculation to both the median nerve and end receptors associated with the Meissner and Pacinian mechanoreceptor systems.

From the results of One Day and Two Day studies, increased vibrotactile sensitivity was consistently seen from one day to the next for 250 and 500 Hz. These frequencies were also affected the most by fingertip skin temperature changes. One of the primary effects of decreased fingertip temperature would be reduced microcirculation in the hand. Based on these results, the idea of increased vibrotactile sensitivity from exercise induced microcirculation increases seems plausible. In the statistically significant models, increased exposure duration was associated with increased vibrotactile sensitivity. This observation further supports the idea of an exercise induced effect.

From the results of this study, it is hypothesized vibrotactile sensitivity is based on a combination of the factors mentioned above. Sustained awkward postures will lead to increased intracarpal pressure and decreased vibrotactile sensitivity over a day. Neutral postures with occasional exertions to extreme wrist postures may lead to increased vibrotactile sensitivity over a day. Dynamic activities may increase intracarpal pressures, but may also be simultaneously increasing microcirculation. Only by continuously measuring these parameters over a work day can true worker exposure be evaluated.

Grip force and direct contact pressures on the carpal tunnel were not evaluated in this study. However, they must be measured over a work day if a better understanding of vibrotactile sensitivity changes is to be achieved. All the workers in this study used various level of grip force during the day. Furthermore, many workers using pneumatic and hand tools created direct compression of the carpal tunnel. From the limited previous research data, the result of increased grip force and direct compression would be increased intracarpal pressures and decreased vibrotactile thresholds if maintained for a long enough period of time. For the current study, the effect of grip force and direct compression were included as random variation in the analysis.

Vibration effects were also not controlled in this study. Direct vibration is known to decrease vibrotactile sensitivity and increase grip strength. Previous research has shown the effects of the decreased vibrotactile sensitivity are quickly dissipated once the subject is removed from the vibratory source. Most workers had at least 10 minutes away from a vibratory source prior to being tested. Some researchers have recommended at least 24 hours away from strong vibratory sources prior to vibrotactile threshold testing. It is possible vibration induced effects artificially skewed the data for individuals using pneumatic tools. Further research will be needed to fully quantify the effect in terms of CVSs.

The primary difficulty with the DataGlove system is adequate calibration. The system relies on manual goniometry as the "gold standard" for calibration. Accurate angle measurements with the goniometer are dependent on good landmark identification and the skill of the individual using the goniometer. Good landmark identification was not easy since the subject was wearing a glove during calibration.

The choice of using the extreme passive range of motions as the calibration points was made to minimize potential calibration errors near neutral wrist postures. Therefore, confidence in the DataGlove measurements are less for extreme postures. To compensate for these potential calibration induced measurement errors large category widths (± 20°) were chosen. In this way, general trends could be initially explored.

The choice of EVA plot widths for wrist postures were determined mainly by this potential measurement error. As calibration based errors decrease through improved procedures, category widths could be decreased further increasing the resolution of the EVA plots. Further refined EVA plots could also use different categories for FE and RU. Results from this study show radial deviations above 30° are unlikely and categories for those ranges are unnecessary. The current choice for continuous time categories should be maintained. The current categories seem to differentiate between static and dynamic wrist movements.

In summary, this study demonstrated the usefulness of full period goniometric sampling and EVA plots to describe individual worker wrist motions. Distinct individual differences in wrist profiles were observed. The general associations between various summary measures and CVSs indirectly support the elevated intracarpal pressure theory of CTS development. Further research with more varied tasks, increased sample size, and introduction of continuous force measurements are needed to validate these findings.

XI. CONCLUSIONS

The following conclusions can be drawn from the One Day, Two Day, and Vibrometry and Goniometry studies:

1. **Vibrotactile threshold measurements are imprecise**. Using the test methodology described in this study, a typical vibrotactile threshold measurement has an average uncertainty around ± 2.5 dB per test independent of frequency. Under a worst case scenario, crosshift vibrometry measurements could vary up to ± 5.0 dB due to measurement accuracies alone. This variation is due to both intratrial and intertrial effects. Furthermore, the Bruel and Kjaer device does not standardize the number of VDT and VPT measurements per test. Individuals with quick reaction times would simultaneously have greater number of VDTs and VPTs associated with their vibrotactile threshold measurement and lower standard deviation. Results of this study indicate there was no significant difference between CVSs of those workers with slow and fast reaction times. However, this issue should be explored further.

2. **CVS effects are small and frequency dependent**. For the lowest frequency (31.5 Hz), a strong shop effect was present. The shop effect was consistent from day to day. Engine shop personnel consistently had increased vibrotactile sensitivities compared to the other groups which had little change or decreased sensitivity. At the highest frequencies (250, 500 Hz), CVS scores from day to day were correlated without any specific physical stressor besides exposure duration and crosshift fingertip temperature.

3. **The small treatment effect coupled with large measurement variations make CVSs suitable only for large scale epidemiological studies**. Sample size calculations based on this results of this study indicate a minimum of 51 people would be needed for

high frequency testing (> 125 Hz) and close to 6000 (5942) people would be needed for 31.5 Hz testing. It is not suitable in its current form as an exposure assessment tool for small sample size identification of potential CTS risk in a workplace. Perhaps by establishing a maximum standard error for vibrotactile threshold measurements, the potential usefulness of this as an exposure tool in individual workplaces may increase.

4. **Exposure duration and crosshift fingertip temperature exerted their greatest influence at the highest frequencies (250, 500 Hz)**. To achieve increased measurement accuracy, these factors must measured and probably controlled. Temperature effects occurred despite attempts to keep fingertip skin temperatures above 29° C.

5. **Age and Sex do not need to be included as independent factors in crosshift vibrometry studies**. This study confirmed the use of pneumatic tools does affect crosshift vibrometry measurements. However, this study did not measure exposure and recovery times while using pneumatic tools. Until this effect can be studied and quantified, pneumatic tool use during testing should be standardized or eliminated.

6. **Electrogoniometry is an emerging technology which will be extremely valuable in quantifying wrist motion over a work shift**. By using a DataGlove, true individual exposure can be measured rather than estimated by videotape or checklist observational studies. The accuracy of the DataGlove is dependent on proper fit of the glove (i.e. sensor orientation), accuracy of the manual goniometer measurements, and the differences in pronation/supination during calibration and the actual work tasks. Proper sensor orientation is critical to crosstalk minimization in the system.

7. **The EVA plot is a useful technique for visualizing ergonomic stress in the workplace**. Individuals performing dynamic wrist movement and/or extreme deviations

can be identified quickly. The choice of wrist deviation and continuous time period categories may need to be optimized to help identify specific ergonomic risk factors associated with the development of cumulative trauma disorders.

8. **Linear discriminant analysis demonstrated the three shops could be classified using a combination of MCTFE, SDFE, and MRU**. MCTFE differences had the greatest effect in the classification scheme. Further research with a variety of shops will be needed to show if this relationship is not shop selection specific.

9. **In comparing crosshift vibrometry with goniometer measurements, only CVSs at 31.5 and 500 Hz demonstrated significant relationships**. At these frequencies, two significant models emerged. A model based on intracarpal pressures was proposed to explain the differences in CVSs. Sustained awkward postures would lead to decreased vibrotactile sensitivities. Dynamic exercise around the neutral posture may lead to increased vibrotactile sensitivities due to increased microcirculation in the median nerve and end receptors. The combination of these factors along with duration/recovery information, grip force, hand-arm vibration, and direct compression of the carpal tunnel may ultimately be needed to explain CVS variations and the potential for CTS development.

APPENDIX A: TABLES

CVSs					
Frequency (Hz)	*N*	*LSN*	*Mean (dB)**	*Standard Deviation (dB)*	*p-value*
31.5	121	5942	0.10	4.73	0.82
125	89	51	1.26	5.40	0.03
250	120	51	1.59	6.91	0.01
500	118	40	1.71	6.58	<0.01

$$\boxed{\sqrt{LSN} = \frac{t_{.05,n-1} \times S_d}{\bar{d}}}$$

LSN = The minimum sample size to achieve a significant effect given the estimated treatment difference and standard deviation

* A positive CVS indicates increased vibration sensitivity from morning to afternoon

Table 1. Crosshift Vibrometry Scores (CVSs) across all subjects at the four measured frequencies. CVSs increased, on average, as frequency increased. The relationship between LSN and frequency was just the opposite.

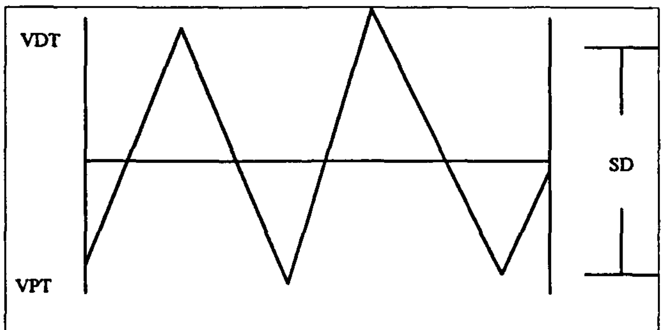
CVS Correlations				
Frequency (Hz)	125	250	500	AllDiff
31.5	.23 (.03)	.23 (.01)	.17 (.06)	.50 (<.01)
125		.70(<.01)	.35 (<.01)	.79 (<.01)
250			.61 (<.01)	.88 (<.01)
500				.77 (<.01)

( )=p-value

Table 2. Pearson product-moment correlations for One Day study. Significant correlations were observed at 125, 250, and 500 Hz.

*Intratrial CVS Standard Deviation (SD)**				
Frequency (Hz)	*N*	*SD Median*	*SD Mean*	*SD SD*
31.5 morning trial 1	88	7.00	7.13	2.53
31.5 morning trial 2	88	7.00	7.63	2.52
31.5 morning trial 3	87	7.00	7.89	2.83
31.5 afternoon trial 1	88	7.00	7.11	2.31
31.5 afternoon trial 2	88	7.00	7.52	2.90
31.5 afternoon trial 3	87	7.00	7.55	2.99
125 morning trial 1	87	6.00	6.48	2.15
125 morning trial 2	86	7.50	7.69	2.38
125 morning trial 3	85	7.00	7.60	2.66
125 afternoon trial 1	87	6.00	6.54	2.63
125 afternoon trial 2	87	7.00	7.02	2.87
125 afternoon trial 3	86	7.00	7.52	2.83
250 morning trial 1	87	7.00	7.18	2.55
250 morning trial 2	87	7.00	7.69	2.93
250 morning trial 3	86	7.00	7.31	2.57
250 afternoon trial 1	88	6.00	6.86	2.78
250 afternoon trial 2	87	7.00	6.89	2.78
250 afternoon trial 3	87	7.00	7.16	2.67
500 morning trial 1	85	6.00	6.44	2.67
500 morning trial 2	82	6.00	6.95	2.38
500 morning trial 3	83	8.00	7.73	2.82
500 afternoon trial 1	86	6.00	6.63	2.71
500 afternoon trial 2	86	6.00	6.74	2.72
500 afternoon trial 3	85	7.00	7.28	2.97

* Units in dB



Definition of Standard Deviation (SD) in Context of Table

Table 3. Mean, median, and standard deviation (SD) of the intratrial standard deviations. Each SD was calculated using six trials per frequency per day (three in morning and three in afternoon). These results indicate intratrial SD is not frequency dependent.

CVS By Average Subject Standard Deviation Over Six Trials					
Frequency (Hz)	*N*	*Less Than 7 dB*	*N*	*Greater Than 7 dB*	*p-value*
31.5	43	0.28	46	0.60	0.74
125	45	0.22	44	2.32	0.07
250	42	1.25	46	1.86	0.67
500	45	2.47	41	1.33	0.37

Table 4. CVSs versus average intratrial standard deviation for two treatment conditions (less than 7 dB, greater than 7 dB). Larger intratrial standard deviations are indicative of slower individual response time to vibration. No significant effects or general trends were noted at any tested frequency.

*Intertrial CVS Standard Deviation (SD)**				
Frequency (Hz)	*N*	SD_{Median}	SD_{Mean}	SD_{SD}
31.5 morning	89	2.52	2.94	2.02
31.5 afternoon	89	2.08	2.61	2.47
125 morning	88	3.06	3.55	2.28
125 afternoon	89	2.65	3.02	1.88
250 morning	88	2.52	3.16	2.25
250 afternoon	88	2.00	2.35	1.56
500 morning	86	2.41	2.76	2.93
500 afternoon	88	2.31	2.81	2.06

* Units in dB

Table 5. Mean, median, and standard deviation (SD) of the intertrial CVS standard deviations. Each SD was calculated using the average vibrotactile threshold data per frequency and test (i.e. three trials per frequency and test). From this data, intertrial CVS standard deviations are not frequency dependent.

CVS Linear Regression Models					
Frequency (Hz)	*N*	*Intercept (dB)*	*Crosshift Temperature (° C)*	*p-value*	R^2
31.5	121	0.35	0.33	0.14	*
125	89	1.21	-0.06	0.85	*
250	120	0.93 (.16)	-0.87	<.01	0.06
500	118	0.66 (.26)	-1.42	<.01	0.18

Frequency (Hz)	*N*	*Intercept (dB)*	*Exposure Duration (min)*	*p-value*	R^2
31.5	121	-1.32	0.004	0.58	*
125	89	0.82	0.001	0.91	*
250	120	-5.36 (.16)	0.018	0.06	0.03
500	118	-6.62 (.07)	0.022	0.02	0.05

( ) = p-value
* = Not Significant

Table 6. Linear regression models of CVS, exposure duration, and crosshift temperature as independent factors. At the highest frequencies (250, 500 Hz), CVS was weakly associated with both independent factors.

CVS Linear Regression Models							
Frequency (Hz)	*N*	*Intercept (dB)*	*Exposure Duration (min)*	*Crosshift Temperature (° C)*	*Interaction*	*p-value*	R^2
31.5	120	-0.464	0.002	2.116	-0.004	0.219	*
125	89	2.837	-0.004	4.158	-0.011	0.197	*
250	120	-3.241	0.011	2.83	-0.009 (.05)	0.003	0.114
500	118	-4.428	0.014	2.118	-0.009 (.04)	<.001	0.245
Frequency (Hz)	*N*	*Intercept (dB)*	*Exposure Duration (min)*	*Crosshift Temperature (° C)*	*Interaction*	*p-value*	R^2
250	120	-5.167 (.16)	0.016 (.10)	-0.828 (.01)	N/A	0.006	0.084
500	118	-6.275 (.06)	0.018 (.03)	-1.366 (<.01)	N/A	<.001	0.215
500 Standardized	118	1.759	1.176	-2.686	N/A	-	0.215
( )=Coefficient p-value							

Table 7. Multi-factor linear regression models of CVS, exposure duration, and fingertip crosshift temperature. At the highest frequencies, exposure duration and temperature were significant. Based on the standardized variable analysis, temperature had the greatest relative effective on CVSs.

CVS By Sex							
Frequency (Hz)	*N*	*Men*	*N*	*Women*	*p-value*		
31.5	82	0.44	39	-0.60	0.26		
125	66	1.26	24	1.24	0.98		
250	81	2.14	39	0.44	0.21		
500	79	2.40	39	0.33	0.11		
CVS By Day of Week							
Frequency (Hz)	*Monday*	*Tuesday*	*Wednesday*	*Thursday*	*Friday*	*Saturday*	*p-value*
31.5	0.75	0.38	0.76	-1.99	-0.01	-1.44	0.47
125	1.64	-0.02	2.08	0.36	2.18	N/A	0.65
250	3.04	0.72	3.08	0.04	-0.14	1.39	0.48
500	2.31	0.50	2.86	4.04	1.84	-2.67	0.19
CVS By Day of Week (Sample Size)							
Frequency (Hz)	*Monday*	*Tuesday*	*Wednesday*	*Thursday*	*Friday*	*Saturday*	
31.5	24	29	29	13	17	9	
125	22	22	21	11	14	0	
250	24	29	28	13	17	9	
500	24	28	27	13	17	9	
CVS By Testing Order							
Frequency (Hz)	*N*	*p-value*					
31.5	121	0.18					
125	89	0.60					
250	120	0.55					
500	118	0.89					

Table 8. One-way ANOVA models comparing CVS to sex, subject testing order (based on month, day, and morning testing time), and day of week tested. No significant effects were observed.

Morning Vibrotactile Threshold By Age					
Frequency (Hz)	*N*	*Intercept (dB)*	*Age (Years)*	*p-value*	R^2
31.5	121	101.80	0.16	<.01	0.07
125	89	99.54	0.31	<.01	0.14
250	120	106.75	0.34	<.01	0.12
500	118	124.84	0.31	<.01	0.11

Table 9. Linear regression models comparing morning vibrotactile thresholds to age. All models were statistically significant ($p<.01$). Morning vibrotactile thresholds were weakly associated with age at all frequencies. Further, the effect was greater at the higher frequencies (125, 250, 500 Hz) than 31.5 Hz. Increased age led to decreased vibrotactile thresholds.

CVS By Age				
Frequency (Hz)	*N*	*Intercept (dB)*	*Age (Years)*	*p-value*
31.5	121	-2.288	0.059	0.129
125	89	0.937	0.008	0.881
250	120	-0.098	0.042	0.464
500	118	1.814	-0.002	0.964

Table 10. Linear regression models comparing CVSs and age. In contrast to the morning vibrotactile threshold results, no association was observed between CVSs and age.

N	52						
Tests Per Subject	4						
Total Vibrograms	208						
Sex	*Male*	*Female*					
	36	16					
Shop Name	*Commissary*	*B-52 Spoiler*	*Engine*	*KC-135 Flight*	*KC-135 Panel*		
Number of Subjects	15	5	9	10	13		
Medical Status	*Yes*	*No*					
Diabetic	7	45					
Diagnosed CTS (No Surgery)	1	51					
Pregnant	0	52					
Day of Week Tested	*Monday*	*Tuesday*	*Wednesday*	*Thursday*	*Friday*		
Day 1	19	10	13	8	2		
Day 2	15	19	15	2	1		
Summary Statistics	*Mean*	*Minimum*	*Maximum*	*Standard Deviation*	*25%*	*50%*	*75%*
Age	43.3	18	60	9.8	38	41	52
xposure Duration (Day 1) (minutes)	378.6	238	457	50.1	349.8	393.5	413
xposure Duration (Day 2) (minutes)	383.6	224	479	63.3	351.3	407.5	428.5

Table 11. Summary of test population and testing conditions for Two Day study.

CVS By Day and Frequency				
Frequency (Hz)	*N*	*Mean (dB)*	*Standard Deviation (dB)*	*p-value*
31.5 Day 1	52	0.16	4.82	0.81
125 Day 1	52	0.96	5.43	0.21
250 Day 1	52	1.40	6.70	0.14
500 Day 1	49	1.20	5.97	0.16
31.5 Day 2	52	0.53	3.66	0.31
125 Day 2	52	0.72	5.56	0.35
250 Day 2	51	1.80	6.11	0.04
500 Day 2	52	1.64	5.80	0.05*
* Distribution was non-normal.				
p-value using signed-ranks test was 0.07				

Table 12. CVSs across all subjects and fequencies for both days of testing. Statistical significance at the higher frequencies was not as consisistent as the One Day study, but the overall trend was similar.

CVS Correlations				
Frequency (Hz)	*125 Day 1*	*250 Day 1*	*500 Day 1*	*All Day 1*
31.5 Day 1	.22 (.11)	.15 (.30)	.12 (.43)	.45 (<.01)
125 Day 1		.68 (<.01)	.44 (<.01)	.80 (<.01)
250 Day 1			.74 (<.01)	.90 (<.01)
500 Day 1				.81 (<.01)
	125 Day 2	250 Day 2	500 Day 2	All Day 2
31.5 Day 2	.11 (.45)	.14 (.34)	.16 (.27)	.37 (.01)
125 Day 2		.71 (<.01)	.60 (<.01)	.84 (<.01)
250 Day 2			.66 (<.01)	.89 (<.01)
500 Day 2				.85 (<.01)
( ) = p-value				

Table 13. Pearson product-moment correlations for the Two Day study. Results are similar to the One Day study. No significant correlations were observed between 31.5 Hz CVS and the higher frequencies

Temperature Summary (N=52)					
Temperature (° C)	*Mean*	*Standard Deviation*	*Median*	*Minimum*	*Maximum*
Crosshift Day 1	-0.38	2.01	-0.25	-6.05	5.05
Crosshift Day 2	-0.44	1.60	-0.58	-4.40	3.15
Morning Temperature Day 1	31.63	1.82	31.75	27.15	34.65
Morning Temperature Day 2	31.99	1.54	32.25	27.45	34.80
Afternoon Temperature Day 1	32.01	1.92	32.22	26.70	35.10
Afternoon Temperature Day 2	32.40	1.20	32.40	29.50	34.50

Table 14. Absolute and crosshift fingertip skin temperature measurments for the Two Day study. In general, fingertip skin temperatures were maintained above 29 °C.

CVS						
Frequency (Hz)	*N*	*Intercept*	*Exposure Duration (min)*	*Crosshift Temperature (°C)*	*p-value*	R^2
31.5 Day 1	52	2.500	-0.006		0.651	
125 Day 1	52	-0.071	0.003		0.860	
250 Day 1	52	-0.751	0.006		0.765	
500 Day 1	49	-2.324	0.009		0.588	
31.5 Day 1	52	0.293		0.347	0.304	
125 Day 1	52	0.895		-0.158	0.680	
250 Day 1	52	0.959		-1.148	0.012	0.120
500 Day 1	49	0.657		-1.527	<.001	0.281
31.5 Day 1	52	2.913	-0.007	0.356	0.520	
125 Day 1	52	-0.259	0.003	-0.162	0.901	
250 Day 1	52	-2.097	0.008	-1.158	0.040	0.123*
500 Day 1	49	-4.460	0.014	-1.549	<.001	0.294*
31.5 Day 2	52	-0.462	0.003		0.754	
125 Day 2	52	0.546	0.000		0.970	
250 Day 2	51	6.786	-0.013		0.344	
500 Day 2	52	-0.003	0.004		0.743	
31.5 Day 2	52	0.577		0.118	0.717	
125 Day 2	52	0.727		0.005	0.991	
250 Day 2	51	1.494		-0.741	0.171	
500 Day 2	52	1.000		-1.434	0.004	0.157
31.5 Day 2	52	-0.570	0.003	0.133	0.878	
125 Day 2	52	0.539	0.000	0.008	0.999	
250 Day 2	51	7.329	-0.015	-0.809	0.210	
500 Day 2	52	1.159	0.000	-1.436	0.015	0.157*

* Interaction term (Exposure Duration * Crosshift Temperature) and Exposure Duration coefficient were not significant in full factorial model

Table 15. Linear regression models for the Two Day study using CVS, crosshift fingertip temperature, and exposure duration. Crosshift fingertip temperature was the only significant independent factor in the models.

CVS (dB) vs Sex							
Frequency (Hz)	*Men*	*Women*	*p-value*				
31.5 Day 1	0.57	-0.77	0.36				
125 Day 1	0.86	1.17	0.85				
250 Day 1	2.50	-1.08	0.08				
500 Day 1	1.45	0.64	0.67				
31.5 Day 2	0.56	0.46	0.93				
125 Day 2	1.48	-0.98	0.14				
250 Day 2	2.17	0.98	0.52				
500 Day 2	2.36	0.00	0.18				
CVS (dB) vs Day of Week							
Frequency (Hz)	*Monday*	*Tuesday*	*Wednesday*	*Thursday*	*Friday*	*p-value*	R^2
31.5 Day 1	1.00	2.07	-1.44	-1.13	-1.18	0.35	
125 Day 1	2.18	-0.73	0.87	0.92	-1.50	0.69	
250 Day 1	3.16	-1.30	1.10	1.04	1.50	0.58	
500 Day 1	1.75	0.58	-1.19	3.79	2.50	0.45	
31.5 Day 2	-0.13	0.58	1.16	0.33	0.33	0.93	
125 Day 2	1.84	-2.32	2.27	6.50	7.00	0.02	0.21*
250 Day 2	3.09	0.58	1.67	3.33	4.33	0.80	
500 Day 2	2.36	0.49	1.24	8.50	4.67	0.40	

* Even though model is significant, no significant pairwise differences were present.

Table 16. One-way ANOVA models comparing CVS, sex, and day of week tested for the Two Day study. Sex and day of week tested were not significantly associated with CVSs.

CVS vs Age				
Frequency (Hz)	*N*	*Intercept (dB)*	*Age (Years)*	*p-value*
31.5 Day 1	52	-0.80	0.02	0.75
125 Day 1	52	-0.21	0.03	0.73
250 Day 1	52	-1.64	0.07	0.47
500 Day 1	49	1.68	-0.01	0.90
31.5 Day 2	52	-0.83	0.03	0.56
125 Day 2	52	-3.53	0.10	0.22
250 Day 2	51	-0.88	0.06	0.48
500 Day 2	52	5.27	-0.08	0.32

Table 17. Linear regression models comparing CVS with age. No significant association was observed between CVS and age at any frequency or day of testing.

CVS (dB) vs Shop Name							
Frequencies (Hz)	*KC-135 Panel*	*KC-135 Flight*	*Commissary*	*Engine*	*B-52 Spoiler*	*p-value*	R^2
31.5 Day 1	-1.82	-1.73	0.82	4.74	-1.13	0.01	0.25
125 Day 1	-1.26	0.23	2.24	2.33	1.80	0.44	*
250 Day 1	-1.54	-0.20	1.36	6.15	3.80	0.08	0.16
500 Day 1	-2.28	1.67	1.58	4.67	1.47	0.12	*
31.5 Day 2	-0.13	0.17	0.56	3.04	-1.67	0.16	*
125 Day 2	0.82	0.67	1.13	1.22	-1.53	0.92	*
250 Day 2	-0.75	1.50	4.40	2.44	-0.47	0.23	*
500 Day 2	1.49	2.20	1.89	0.85	1.53	0.99	*
* = Not significant							

CVS (dB) vs Shop Categories								
Frequencies (Hz)	*N*	*Commissary*	*N*	*Engine*	*N*	*Sheetmetal*	*p-value*	R^2
31.5 Day 1	15	0.82	9	4.74	28	-1.67	<.01	0.24
125 Day 1	15	2.24	9	2.33	28	-0.18	0.27	*
250 Day 1	15	1.36	9	6.15	28	-0.11	0.05	0.12
500 Day 1	15	1.58	9	4.67	28	-0.27	0.10	*
31.5 Day 2	15	0.56	9	3.04	28	-0.30	0.06	0.11
125 Day 2	15	1.13	9	1.22	28	0.35	0.87	*
250 Day 2	15	4.40	9	2.44	27	0.14	0.09	*
500 Day 2	15	1.89	9	0.85	28	1.75	0.91	*
* = Not significant								

Table 18. One-way ANOVA models comparing CVS to shop. In the first set of models, all shops were included. In the second set of models, the three sheetmetal shops were combined. Significant shops effects were observed at 31.5 Hz and 250 Hz. However, only the shop effects at 31.5 Hz were consistent from Day 1 to Day 2.

CVS vs Vibration Exposure						
Frequency (Hz)	*N*	*>60 Minutes (dB)*	*N*	*None (dB)*	*p-value*	R^2
31.5 Day 1	19	-1.47	29	1.54	0.02	0.11
125 Day 1	19	-0.03	29	2.07	0.19	*
250 Day 1	19	-0.19	29	2.60	0.18	*
500 Day 1	17	-0.09	28	1.69	0.35	*
31.5 Day 2	23	0.33	26	0.67	0.76	*
125 Day 2	23	1.20	26	0.76	0.90	*
250 Day 2	22	0.17	26	3.65	0.05	0.08
500 Day 2	23	1.49	26	1.95	0.79	*
* = Not significant						

Table 19. One-way ANOVA models comparing CVS to vibration exposure. Two treatment levels of vibration exposure (none, >60 minutes) were used. Vibration was intermittently associated with CVS at two frequencies (31.5, 250 Hz).

CVS vs Hand/Wrist Pain						
Frequency (Hz)	*N*	*No (dB)*	*N*	*Yes (dB)*	*p-value*	R^2
31.5 Day 1	37	0.20	15	0.07	0.93	*
125 Day 1	37	1.79	15	-1.11	0.08	0.06**
250 Day 1	37	1.69	15	0.67	0.62	*
500 Day 1	35	1.73	15	-0.12	0.33	*
31.5 Day 2	37	0.79	15	-0.13	0.41	*
125 Day 2	37	0.14	15	2.16	0.24	*
250 Day 2	37	2.00	14	1.26	0.70	*
500 Day 2	37	2.34	15	-0.11	0.17	*
* = Not significant						
** = Borderline significant						

Table 20. One-way ANOVA models comparing CVS and hand/wrist pain. Hand/wrist pain was defined as work-related and occuring within the previous week. No association between hand/wrist pain and CVS was observed.

Test Order ANOVA Table				
31.5 Hz				
ANOVA R^2 =.73				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Subject	5590.78	109.62	51	<.01
Test Order	33.88	11.29	3	0.51
Skin Temperature (Test Order)	36.41	9.10	4	0.64
125 Hz				
ANOVA R^2 =.83				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Subject	12597.20	247.00	51	<.01
Test Order	142.83	47.61	3	0.05
Skin Temperature (Test Order)	151.08	37.76	4	0.09
250 Hz				
ANOVA R^2 =.84				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Subject	16105.10	315.79	51	<.01
Test Order	286.82	95.61	3	<.01
Skin Temperature (Test Order)	358.07	89.52	4	<.01
500 Hz				
ANOVA R^2 =.85				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Subject	12377.80	242.70	51	<.01
Test Order	82.82	27.61	3	0.15
Skin Temperature (Test Order)	537.96	134.49	4	<.01

Table 21. Multi-factor repeated measures ANOVA models comparing absolute vibrotactile thresholds, subject, test order (Day 1 AM, Day 1 PM, Day 2 AM, Day 2 PM), and fingertip skin temperature. Fingertip skin temperature and test order were significant at the higher frequencies.

Vibrotactile Thresholds by Day and Frequency			
Frequency (Hz)	*Median (dB)*	*Mean (dB)*	*Standard Deviation (dB)*
31.5 Morning Day 1	109.17	108.08	5.72
31.5 Afternoon Day 1	108.33	107.92	6.17
31.5 Morning Day 2	108.83	109.31	6.00
31.5 Afternoon Day 2	108.33	108.78	6.85
125 Morning Day 1	112.50	113.24	8.73
125 Afternoon Day 1	111.00	112.28	8.46
125 Morning Day 2	111.50	113.08	9.42
125 Afternoon Day 2	112.83	112.34	8.96
250 Morning Day 1	125.17	122.62	9.89
250 Afternoon Day 1	121.33	121.22	9.55
250 Morning Day 2	120.33	121.94	9.78
250 Afternoon Day 2	120.00	120.29	10.01
500 Morning Day 1	141.67	139.39	8.50
500 Afternoon Day 1	139.33	138.34	8.57
500 Morning Day 2	138.83	139.29	8.59
500 Afternoon Day 2	137.00	137.65	8.80

Table 22. Summary measures of vibrotactile thresholds per frequency and test order (Two Day study). In general, vibration sensitivity across all subjects increased from morning to afternoon on both days.

CVS Correlations by Day and Frequency				
Frequency (Hz)	*31.5 Day 1*	*125 Day 1*	*250 Day 1*	*500 Day 1*
31.5 Day 2	-.02 (.87)			
125 Day 2		.09 (.52)		
250 Day 2			.40 (<.01)	
500 Day 2				.29 (.04)
( ) = p-value				

Table 23. Pearson product-moment correlations for Day 1 and Day 2 CVSs by frequency. CVSs between days was associated at the highest frequencies (250, 500 Hz).

Day 2 CVS ANACOVA Table				
31.5 Hz (N=52)				
ANACOVA R^2=.42 (p<.01)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day 1 CVS	16.18	16.18	1	0.21
Crosshift Fingertip Temperature	56.45	56.45	1	0.02
Shop Name	85.40	21.35	4	0.09
Day 1 CVS*Shop Name	126.67	31.67	4	0.02
125 Hz (N=52)				
ANACOVA R^2=.21 (p=.37)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day 1 CVS	0.63	0.63	1	0.89
Crosshift Fingertip Temperature	14.26	14.26	1	0.50
Shop Name	54.05	13.51	4	0.77
Day 1 CVS*Shop Name	292.80	73.20	4	0.06
250 Hz (N=51)				
ANACOVA R^2=.33 (p=.06)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day 1 CVS	106.59	106.59	1	0.07
Crosshift Fingertip Temperature	19.23	19.23	1	0.44
Shop Name	178.62	44.66	4	0.24
Day 1 CVS*Shop Name	98.07	24.52	4	0.54
500 Hz (N=49)				
ANACOVA R^2=.19 (p=.55)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day 1 CVS	240.18	240.18	1	0.01
Crosshift Fingertip Temperature	59.56	59.56	1	0.20
Shop Name	55.47	13.87	4	0.81
Day 1 CVS*Shop Name	30.16	7.54	4	0.93

Table 24. ANACOVA table for CVS, crosshift fingertip temperature and shop name. For 31.5 Hz, interaction between Day 1 CVS and shop name was significant.

CVS vs Shop Name, Day Tested, and Crosshift Fingertip Temperature				
31.5 Hz				
ANOVA R^2 =.54				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Shop Name	338.31	84.58	4	<.01
Day Tested	0.89	0.89	1	0.83
Crosshift Fingertip Temperature	47.48	47.48	1	0.12
Subject (Shop Name)	598.00	12.72	47	0.90
Shop Name*Day Tested	62.22	15.56	4	0.51
125 Hz				
ANOVA R^2 =.57				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Shop Name	77.40	19.35	4	0.69
Day Tested	8.50	8.50	1	0.59
Crosshift Fingertip Temperature	3.68	3.68	1	0.72
Subject (Shop Name)	1612.29	34.30	47	0.28
Shop Name*Day Tested	73.86	18.47	4	0.64
250 Hz				
ANOVA R^2 =.75				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Shop Name	344.38	86.10	4	0.14
Day Tested	3.75	3.75	1	0.69
Crosshift Fingertip Temperature	2.24	2.24	1	0.76
Subject (Shop Name)	2245.67	47.78	47	<.01
Shop Name*Day Tested	193.11	48.28	4	0.10
500 Hz				
ANOVA R^2 =.76				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Shop Name	85.57	21.39	4	0.67
Day Tested	6.80	68.00	1	0.55
Crosshift Fingertip Temperature	204.71	204.71	1	<.01
Subject (Shop Name)	1723.75	36.68	47	0.01
Shop Name*Day Tested	113.02	28.25	4	0.67

Table 25. Multi-factor ANOVA comparing CVS, subject, crosshift fingertip temperature, and shop name. Shop effect was significant only at 31.5 Hz. Crosshift fingertip temperature was significant only at 500 Hz.

Commissary CVS Linear Regression Models (N=15)							
Frequencies (Hz)	*ANOVA R^2*	*p-value*	*Intercept (dB)*	*Scanner Time (min)*	*Items Scanned*	*Scan Rate*	*Crosshift Temperature (° C)*
31.5 Day 1	0.40	0.23					
125 Day 1	0.31	0.40					
250 Day 1	0.13	0.81					
500 Day 1	0.19	0.69					
31.5 Day 2	0.24	0.56					
125 Day 2	0.66	0.02	3.41 (.72)	0.25 (.91)	.005 (.01)	-.84 (<.01)	.49 (.40)
250 Day 2	0.60	0.04	-14.95 (.13)	3.06 (.19)	.004 (.03)	-.38 (.09)	-.45 (.42)
500 Day 2	0.49	0.12					
( ) = coefficient p-value							

Table 26. Linear regression models for Two Day study using commissary personnel only. Models compared CVS, scan rate, items scanned, scanner time, and crosshift fingertip temperature. An association between items scanned, scan rate, and CVS was observed intermittently at the higher frequencies (125, 250 Hz).

Commissary CVS ANOVA Table (N=15)				
31.5 Hz				
ANOVA R^2 =.44 (p=.95)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day Tested	1.14	1.14	1	0.81
Scanner Time	52.79	52.79	1	0.12
Items	25.05	25.05	1	0.27
Scan Rate	0.80	0.80	1	0.84
Crosshift Temperature	4.84	4.84	1	0.62
Subject	83.19	5.94	14	0.97
125 Hz				
ANOVA R^2 =.44 (p=.95)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day Tested	27.14	27.14	1	0.48
Scanner Time	8.54	8.54	1	0.69
Items	48.12	48.12	1	0.35
Scan Rate	3.30	3.30	1	0.80
Crosshift Temperature	4.95	4.95	1	0.76
Subject	302.86	21.63	14	0.92
250 Hz				
ANOVA R^2 =.67 (p=.48)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day Tested	16.19	16.19	1	0.47
Scanner Time	2.07	2.07	1	0.79
Items	52.35	52.35	1	0.21
Scan Rate	11.09	11.09	1	0.55
Crosshift Temperature	30.37	30.37	1	0.33
Subject	394.50	28.18	14	0.53
500 Hz				
ANOVA R^2 =.75 (p=.22)				
Effect Test				
Source	*SS*	*MS*	*df*	*p-value*
Day Tested	0.02	0.02	1	0.98
Scanner Time	2.00	2.00	1	0.78
Items	23.13	23.13	1	0.35
Scan Rate	0.65	0.65	1	0.87
Crosshift Temperature	56.77	56.77	1	0.15
Subject	428.14	30.58	14	0.35

Table 27. Multi-factor ANOVA models comparing CVS, scanner time, items scanned, and scan rate for commissary personnel only. Fifteen people were tested. No significant association between CVS and the various factors was observed. However, the power of the test is low due to small sample size and multiple factors tested in the model.

Goniometry and Vibrometry Time Data								
					Vibrometry Test	*Goniometry Test*		
Subject	**Group**	**Sex**	**Start Time**	**End Tim**	*Interval (min)*	*Interval (min)*	***%Recorded***	***BreakTime (min)***
1	Commissary	f	10:18	14:44	266	229	86	10
2	Commissary	f	9:35	15:28	353	313	89	60
3	Commissary	m	9:48	14:08	260	226	87	10
4	Commissary	m	9:22	15:16	354	281	79	80
5	Commissary	f	9:33	14:32	299	258	86	60
6	Commissary	m	9:18	15:18	360	333	93	75
7	Engine	m	8:27	14:07	340	323	95	80
8	Engine	m	8:19	14:29	370	354	96	80
9	Engine	m	8:29	14:25	356	335	94	130
10	Engine	m	8:18	13:30	312	152	49	30
11	Engine	m	8:08	14:26	378	344	91	90
12	KC-135Panel	m	7:39	10:33	174	105	60	0
13	KC-135Panel	m	10:18	14:26	248	236	95	75
14	KC-135Panel	m	8:29	14:38	369	352	95	95
15	KC-135Panel	f	8:50	14:24	334	324	97	60
16	KC-135Panel	f	8:57	14:30	333	320	96	60

Table 28. Vibrometry and Goniometry study summary test parameters.

Linear Regression Models: Data Glove Calibration						
Pronation	*N*	*Deviation*	R^2	*p-value*	*Intercept*	*Goniometer*
0	9	RU	0.94	<.01	146.97	-1.76
30	9	RU	0.96	<.01	148.94	-2.60
60	11	RU	0.97	<.01	137.12	-2.16
90	11	RU	0.99	<.01	136.52	-2.26
90	15	FE	0.98	<.01	129.00	-1.03
All intercepts and coefficients are statistically significant ($p<.05$)						

Table 29. Linear regression models showing the accuracy of the DataGlove compared to manual goniometer measurements. R^2 values for the models ranged from .94 to .98.

Percentage Working Time Spent (Average Shop Response)										
Wrist FE										
Shop Name	*N*	*Ext>10*	*Ext>30*	*Flex>10*	*Flex>30*	*Ext/Flex Ratio >10*	*Ext/Flex Ratio >30*	*Dynamic (<1sec)*	*Static (>8 sec)*	*Dyn/Stat Ratio*
Commissary	6	70	33	8	2	8.8:1	16.5:1	48	12	4:1
Engine	5	48	25	25	8	1.9:1	3.1:1	21	36	0.6:1
KC-135 Panel	5	55	20	14	2	3.9:1	10.0:1	18	35	0.5:1
Wrist RU										
Shop Name	*N*	*Uln>10*	*Uln>30*	*Rad>10*		*Uln/Rad Ratio >10*		*Dynamic (<1sec)*	*Static (>8 sec)*	*Dyn/Stat Ratio*
Commissary	6	99	69	<1	N/A	99:1	N/A	28	19	1.5:1
Engine	5	55	13	8	N/A	6.9:1	N/A	13	46	0.3:1
KC-135 Panel	5	67	22	6	N/A	11.2:1	N/A	12	47	0.3:1

Table 30. Percentage working time spent by "average" shop personnel in various wrist deviations and movements. Commissary personnel, on average, performed dynamic movements and kept their wrist in extension and ulnar deviation. In contrast, engine and KC-135 panel personnel performed relatively static movements and kept their wrists in a more neutral postures. Engine shop personnel, on average, had a wider range of wrist motion during the day than KC-135 personnel.

Goniometer Summary Measures								
	Commissary		KC-135 Panel		Engine		One-Way ANOVA	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	ANOVA R^2	p-value
MFE	19.6	6.4	12.3	14.2	9.3	18.8	0.11	0.45
SDFE	21.2	3.4	17.6	3.8	23.4	1.1	0.42	0.03
MCTFE	3.7	0.3	5.2	0.4	5.1	0.2	0.88	<.01
MRU	35.6	5.0	17.9	16.0	11.6	8.4	0.55	0.01
SDRU	12.1	2.9	13.4	4.8	14.0	2.5	0.06	0.66
MCTRU	4.5	0.4	5.7	0.5	5.6	0.1	0.72	<.01

Table 31. Summary of goniometer test measures for three shops tested. MFE is defined as mean wrist deviation in flexion/extension. MRU is defined as mean wrist deviation in radial/ulnar deviation. MCTFE is defined as mean continuous time in flexion/extension. MCTRU is defined as mean continuous time in radial/ulnar deviation. SDFE is defined as the standard deviation associated with the mean wrist deviation in flexion/extension. SDRU is defined as the standard deviation of the mean wrist deviation in radial/ulnar deviation. MFE, MRU, SDFE, SDRU are in degrees. MCTFE and MCTRU are unitless. The lower the MCTFE and MCTRU values, the more dynamic the wrist motions for the shop.

Discriminant Analysis Canonical Variable Coefficients						
Model	*MFE*	*SDFE*	*MCTFE*	*MCTRU*	*MRU*	*SDRU*
Full CV1	0.00	0.13	1.87	-0.12	0.02	0.00
Full CV2	0.00	0.18	0.47	-0.08	0.02	-0.10
Subset CV1		0.14	1.79		0.02	
Subset CV2		0.10	0.05		0.00	
CV1=Canonical Variable 1						
CV2=Canonical Variable 2						

Table 32. Canonical variables coefficients for the full and subset linear discriminant analysis. Each canonical variable is made up different proportions of the orginal goniometer variables.

Single Factor Effects					
Effect	N	ANOVA R^2	p-value	Intercept	Magnitude
TEMPDIFF	16	0.12	0.20	0.10	0.99
TIMEMIN	16	**0.30**	**0.03**	**-16.35**	**0.05**
MCTFE	16	**0.37**	**0.01**	**-18.81**	**4.01**
MCTRU	16	**0.30**	**0.03**	**-23.37**	**4.42**
MFE	16	0.00	0.82	0.00	-0.02
MRU	16	**0.31**	**0.02**	4.18	**-0.20**
SDFE	16	0.02	0.65	3.27	-0.17
SDRU	16	0.02	0.65	2.11	-0.19
Significant effects are in bold ($p<.05$)					

Table 33. Linear regression models at 31.5 Hz comparing CVS to the independent effects of crosshift fingertip temperature (TEMPDIFF), exposure duration (TIMEMIN), MCTFE, MCTRU, MFE, MRU, SDFE, SDRU for the Vibrometry and Goniometry study. CVS was independently associated with TIMEMIN, MCTFE, MCTRU, and MRU.

Correlation Matrix				
	TIMEMIN	*MCTFE*	*MCTRU*	*MRU*
TIMEMIN	1.00	.11 (.69)	.06 (.81)	-.50 (.05)
MCTFE		1.00	.96 (<.01)	-.73 (<.01)
MCTRU			1.00	-.66 (<.01)
MRU				1.00
( ) = p-value				

Table 34. Pearson product-moment correlations for signficant independent effects in Vibrometry and Goniometry study. Significant associations were observed between a) MCTFE and MCTRU (a positive association), b) MCTFE and MRU (a negative association), and c) MCTRU and MRU (a negative association).

Linear Regression Model Summaries (31.5 Hz) (N=16)				
Model Parameters	*Parameters*	*Adjusted R^2*	*R^2*	*p-value*
TIMEMIN,MCTRU,MRU FACTORIAL	7	0.30	0.62	0.20
TIMEMIN,MCTRU,TIMEMIN*MCTRU	3	0.48	0.59	***0.01***
TIMEMIN,MCTRU, MRU	3	0.45	*0.56*	***0.02***
TIMEMIN,MCTRU	2	0.49	**0.56**	**0.01**
TIMEMIN*MCTRU	1	0.48	**0.51**	***<01***
TIMEMIN*MCTFE	1	0.54	**0.57**	***<01***
MCTRU, MRU, MCTRU*MRU	3	0.21	0.37	0.13
MCTRU, MRU	2	0.27	*0.37*	***0.05***
TIMEMIN,MCTFE,MRU FACTORIAL	7	0.42	0.69	0.11
TIMEMIN,MCTFE,TIMEMIN*MCTFE, TIMEMIN*MRU	5	0.46	*0.64*	**0.04**
TIMEMIN,MCTFE,TIMEMIN*MCTFE	4	0.51	*0.64*	***0.02***
TIMEMIN,MCTFE, MRU	3	0.54	*0.63*	***<01***
TIMEMIN, MCTFE	2	0.54	**0.60**	***<01***
MCTFE, MRU, MCTFE*MRU	3	0.26	0.41	0.09
MCTFE, MRU	2	0.31	0.40	***0.04***
Significant effects are in bold ($p<.05$)				

Table 35. Linear regression models at 31.5 Hz comparing CVS to various combinations of TIMEMIN, MCTRU, MCTFE, and MRU. Using the adjusted R^2 criteria for selection of best fit non-nested ANOVA models, CVSs are best associated with TIMEMIN and either MCTFE or MCTRU.

Best Fit Model Coefficients 31.5 Hz CVS (N=16)				
Model Parameters	*Intercept (dB)*	*TIMEMIN*	*MCTFE*	*MCTRU*
TIMEMIN, MCTRU	**-36.97 (<.01)**	**.05 (.02)**		**4.14 (.02)**
TIMEMIN, MCTFE	**-31.51 (<.01)**	**.04 (.02)**	**3.67 (.01)**	
Models With Standardized Variables	*Intercept (dB)*	*TIMEMIN*	*MCTFE*	*MCTRU*
TIMEMIN, MCTRU	-0.33	**2.65**		**2.65**
TIMEMIN, MCTFE	-0.33	**2.51**	**2.89**	
Significant effects in bold (p<.05)				

Table 36. Coefficients associated with TIMEMIN and MCTFE (or MCTRU) linear regression models. All coefficients are positive indicating increased vibration sensitivity is associated with longer exposure times and increasingly static wrist movements. According to the standardized variable linear regression model, TIMEMEN and MCTFE have the same relative effect on CVSs.

Best Fit Model Summaries (31.5 Hz) (N=16)												
Model Parameters	*No.*	*Adjusted R^2*	*R^2*	*p-value*	*Intercept*	*MCTFE*	*MRU*	*SDFE*	*SDFE*MCTFE*	*SDFE*MRU*	*MCTFE*MRU*	*SDFE*MCTFE*MRU*
SDFE, MRU, MCTFE FACTORIAL	7	0.80	0.89	**<.01**	-226.78	47.15	**12.79**	**8.99**	**-1.87**	**-0.58**	**-2.85**	**0.13**
SDFE, MRU, MCTFE, SDFE*MCTFE, SDFE*MRU, MCTFE*MRU	6	0.64	0.78	**0.01**	**158.77**	**-25.41**	-0.43	**-10.11**	1.75	0.07	-0.22	
SDFE, MCTFE, SDFE*MCTFE, MRU, SDFE*MRU	5	0.60	0.74	**0.01**	**197.14**	**-31.87**	-1.71	**-10.20**	**1.71**	0.08		
SDFE, MCTFE, SDFE*MCTFE, MRU	4	0.49	0.63	**0.02**	80.64	-14.98	-0.11	**-4.16**	**0.81**			
SDFE, MCTFE, MRU	3	0.25	0.40	0.10	-8.73	2.58	-0.10	-0.06				
SDFE, MCTFE	2	0.28	0.38	**0.05**	-21.58	**4.15**		0.10				
SDFE, MRU	2	0.26	0.36	0.06	10.62		**-0.21**	-0.30				
SDFE*MRU, MCTFE*MRU, SDFE*MCTFE*MRU, MRU, MCTFE	5	0.72	**0.81**	<.01	-57.33 (.04)	**11.78 (.03)**	**5.91 (<.01)**			**-.22 (<.01)**	**-1.31 (<.01)**	**.05 (<.01)**
SDFE*MRU, MCTFE*MRU, SDFE*MCTFE*MRU, MRU	4	0.58	0.69	<.01	3.59 (.07)		**3.56 (.01)**			**-0.19 (<.01)**	**-0.8 (.01)**	**0.04 (.01)**
Significant effects in bold (p<.05)												

Table 37. Linear regression models at 31.5 Hz comparing CVS to various combinations of SDFE, MRU, and MCTFE. A strong association between CVS and these variables was observed. The best fit linear regression model (with all coefficients significant) involved interaction between SDFE, MRU, and MCTFE.

Linear Regression Model Summaries (500 Hz) (N=16)				
Model Parameters	*No.*	*Adjusted R^2*	*R^2*	*p-value*
TIMEMIN	1	0.16	0.22	0.07
TEMPDIFF	1	-0.01	0.06	0.36
MCTFE	1	0.02	0.09	0.27
MCTRU	1	0.03	0.09	0.25
MFE	1	0.18	0.24	0.06
MRU	1	0.00	0.00	0.92
SDFE	1	-0.03	0.04	0.45
SDRU	1	0.01	0.07	0.31

Table 38. Linear regression models at 500 Hz comparing CVS to the independent effects of TEMPDIFF, TIMEMIN, MCTFE, MCTRU, MFE, MRU, SDFE, SDRU for the Vibrometry and Goniometry study. CVS was not significantly associated with any of the variables. TIMEMIN and MFE were boderline associated with CVSs.

Best Fit Model Coefficients 500 Hz (N=16)								
Model Parameters	*No.*	*Adjusted R^2*	*R^2*	*p-value*	*Intercept*	*TIMEMIN*	*MFE*	*TIME*MFE*
TIMEMIN, MFE, TIMEMIN*MFE	3	0.51	*.61*	<.01	**-27.46 (.03)**	**0.08 (.03)**	0.93 (.17)	0.00 (.25)
TIMEMIN, MFE	2	0.50	**.57**	<.01	**-15.56 (<.01)**	**0.04 (<.01)**	**0.06 (<.01)**	
Models With Standardized Variables					*Intercept*	*TIMEMIN*	*MFE*	
TIMEMIN, MFE	2	.50	.57		0.73	**2.42**	**2.49**	
Significant effects in bold (p<.05)								

Table 39. Linear regression models at 500 Hz comparing CVS to various combinations of TIMEMIN and MFE. A signficant association between CVS, TIMEMIN, and MFE was observed. No interaction between TIMEMIN and MFE was observed. Based on the standardized variable linear regression model, the relative effects of TIMEMIN and MFE on CVS were similar.

Linear Regression Models 500 Hz (N=16)										
Model Parameters	*No.*	*Adjusted R^2*	*R^2*	*p-value*	*Intercept*	*TIMEMIN*	*MCTFE*	*MCTRU*	*TIMEMIN*MCTFE*	*TIMEMIN*MCTRU*
TIMEMIN, MCTRU, TIMEMIN*MCTRU	3	0.16	0.33	0.17	-4.85 (.93)	0.05 (.76)		-1.12 (.91)		0.00 (.92)
TIMEMIN,MCTRU	2	0.23	0.33	0.07	0.76 (.93)	**0.04 (.05)**		-2.18 (.16)		
TIMEMIN, MCTFE, TIMEMIN*MCTFE	3	0.18	0.34	0.16	-9.94 (.81)	0.06 (.65)	-0.29 (.97)		0.00 (.86)	
TIMEMIN, MCTFE	2	0.24	0.34	0.07	-2.64 (.72)	**0.04 (.04)**	-1.81 (.15)			
Significant effects in bold (p<.05)										

Table 40. Linear regression models at 500 Hz comparing CVS, MCTFE, MCTRU, and TIMEMIN. Models involving these variables were significant at 31.5 Hz. At 500 Hz, CVS was not associated with any of the combination of variables.

Best Fit Model Summaries 500 Hz (N=16)												
Model Parameters	*No.*	*Adjusted R^2*	*R^2*	*p-value*	*Intercept*	*MCTFE*	*MRU*	*SDFE*	*SDFE*MCTFE*	*SDFE*MRU*	*MCTFE*MRU*	*SDFE*MCTFE*MRU*
SDFE, MRU, MCTFE FACTORIAL	7	0.36	0.66	0.15	335.89 (.14)	-57.97 (.16)	-5.67 (.42)	-15.76 (.16)	2.75 (.18)	[illegible]	0.76 (.58)	-0.04 (.57)
SDFE, MRU, MCTFE, SDFE*MCTFE, SDFE*MRU, MCTFE*MRU	6	0.41	***0.64***	0.09	**223.04 (.01)**	**-36.74 (<.01)**	-1.80 (.17)	**-10.17 (.01)**	**1.69 (<.01)**	[illegible]	-0.01 (.95)	
SDFE, MCTFE, SDFE*MCTFE, MRU, SDFE*MRU	5	0.47	**0.64**	**0.04**	**224.87 (<.01)**	**-37.04 (<.01)**	**-1.86 (.03)**	**-10.17 (<.01)**	**1.69 (<.01)**	[illegible]		
SDFE, MCTFE, SDFE*MCTFE, MRU	4	0.25	0.45	0.13	**100.10 (.02)**	**-18.96 (.02)**	-0.14 (.24)	**-3.70 (.04)**	**0.72 (.04)**			
SDFE, MCTFE, SDFE*MCTFE	3	0.21	0.37	0.12	**79.41 (.04)**	**-16.27 (.03)**		**-3.37 (.05)**	**0.70 (.04)**			
Standardized Model Parameter	*No.*	*Adjusted R^2*	*R^2*	*p-value*	*Intercept*	*MCTFE*	*MRU*	*SDFE*	*SDFE*MCTFE*	*SDFE*M*		
SDFE, MCTFE, SDFE*MCTFE, MRU, SDFE*MRU	5	0.47	**0.64**	**0.04**	2.80	-1.62	-0.91	-1.65	4.90	4.61		
Significant effects in bold (p<.05)												

Table 41. Linear regression models at 500 Hz comparing CVS to various combinations of SDFE, MRU, and MCTFE. A strong association between CVS and these variables was observed. The best fit linear regression model (with all coefficients significant) involved pairwise interaction between a) SDFE and MRU and b) SDFE and MCTFE. The standardized variable linear regression model showed the relative effect of the interaction terms was larger than the independent effects.

APPENDIX B: FIGURES

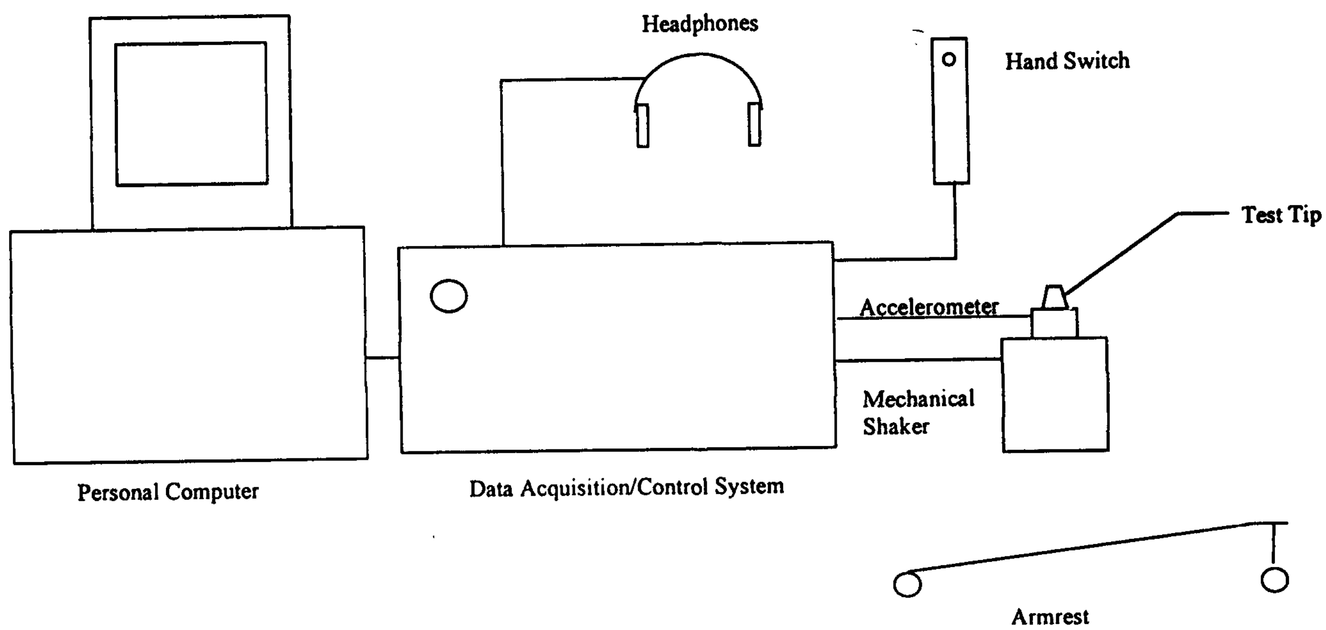


Figure 1. Bruel and Kjaer vibrometer major components.

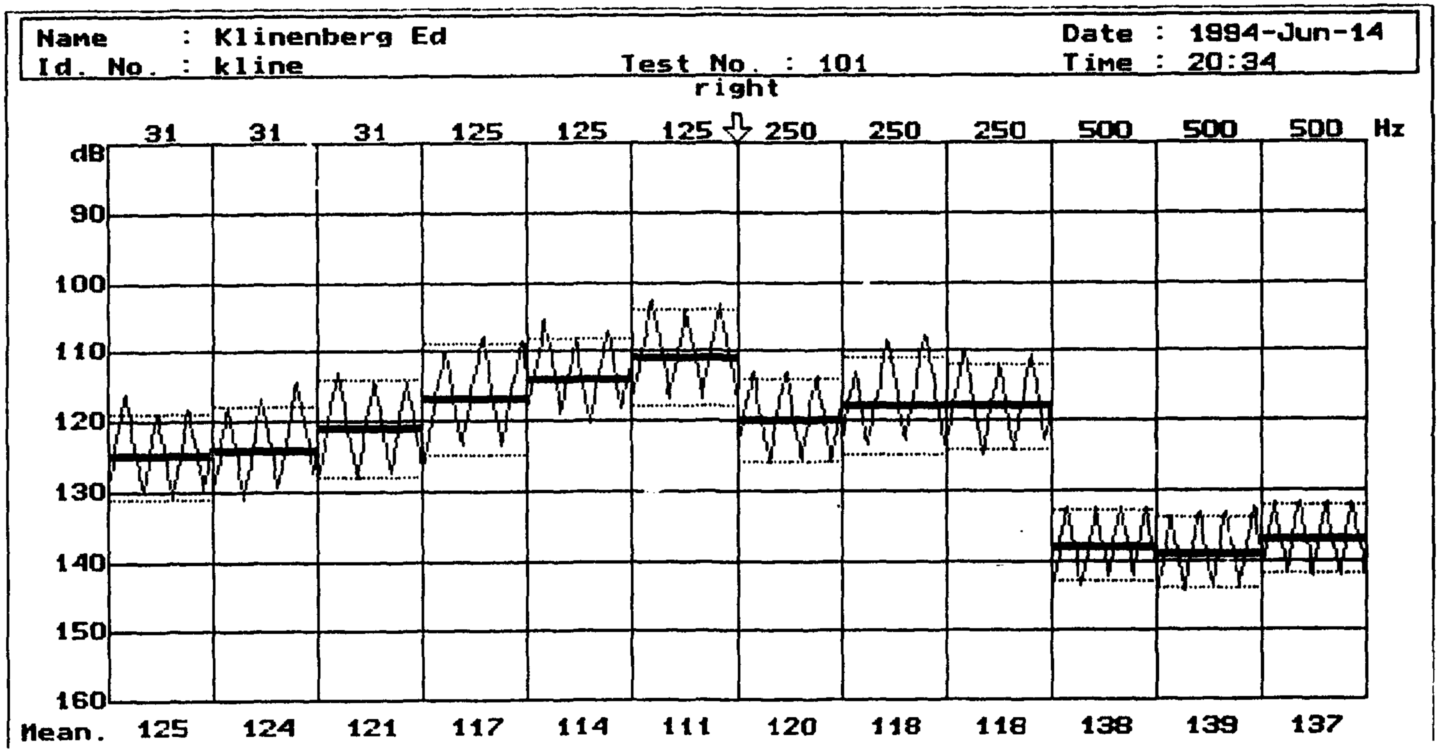


Figure 2. Typical vibrogram using One and Two Day studies protocol. Mean value for each frequency corresponds to the boldface horizontal line. Dotted lines for each frequency correspond to the standard deviation of the VDTs and VPTs. "Zig-zag" line corresponds to actual test tracing for each frequency.

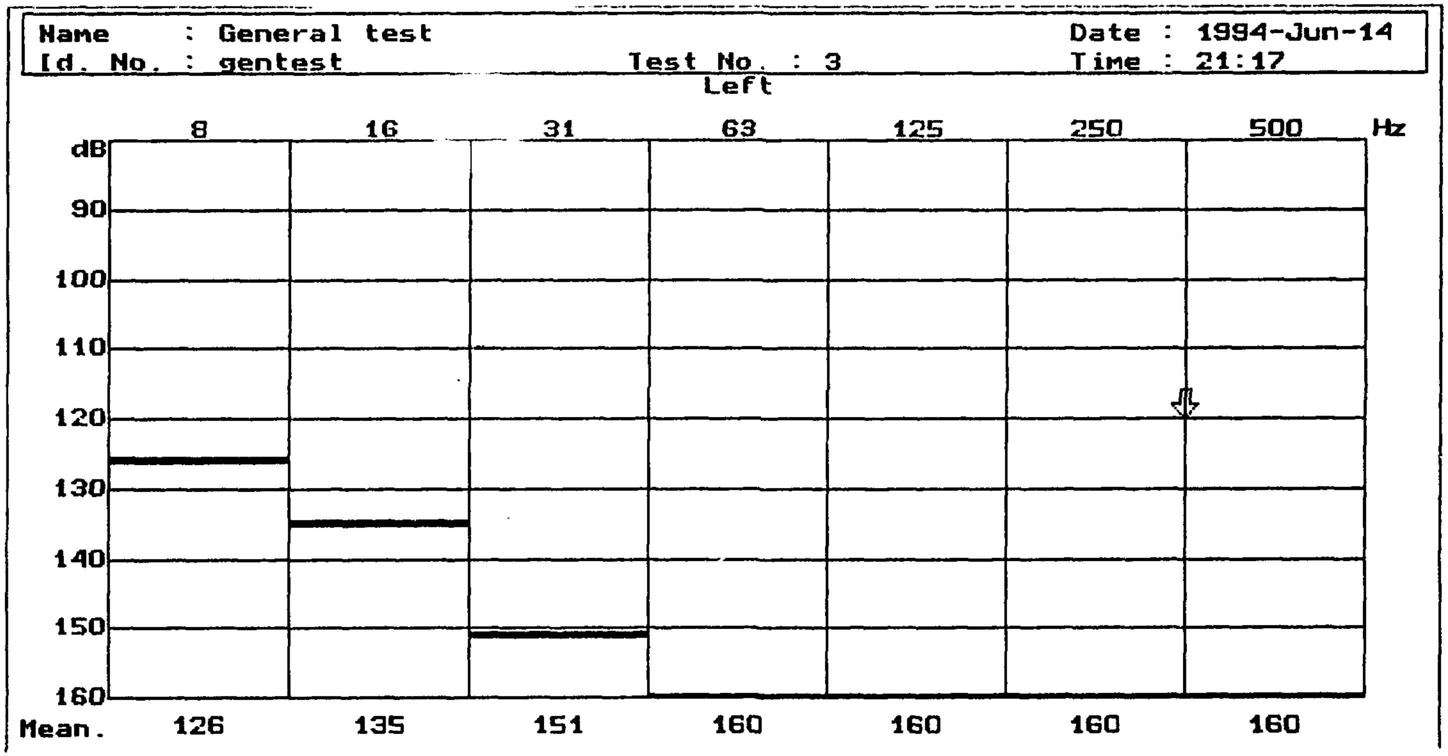


Figure 3. Vibration amplitude ranges for the seven octave band frequencies between 8-500 Hz. Note full amplitude range (80-160 dB) exits only above 63 Hz. Lower frequencies have a more limited amplitude range. The upper amplitude level at the highest frequencies (250 and 500 Hz) was a problem with individuals who had high vibrotactile thresholds (i.e. decreased vibration sensitivity).

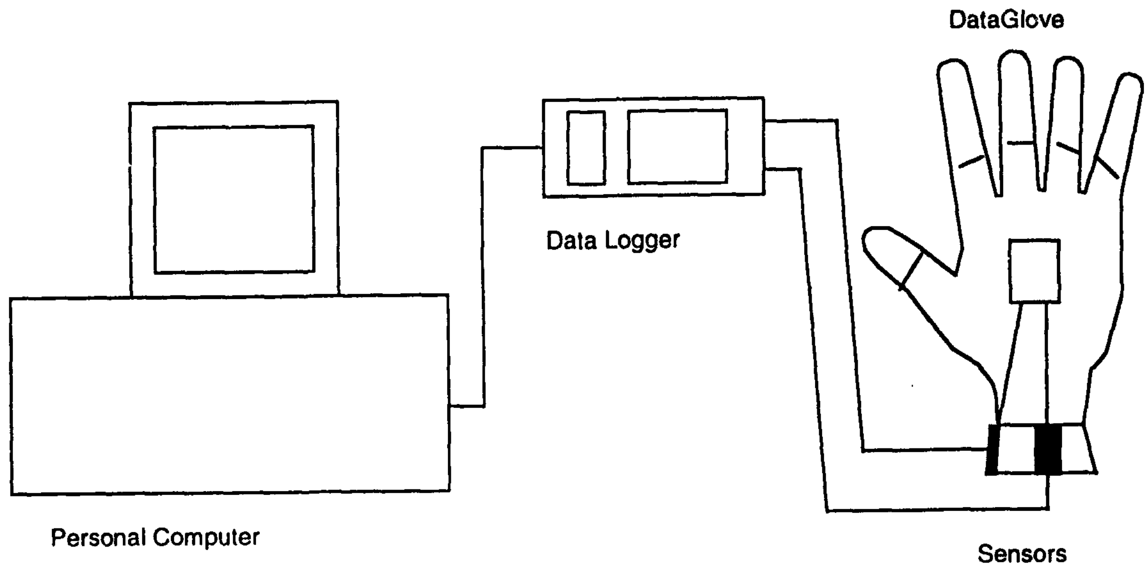


Figure 4. Major components of the DataGlove. DataGlove consists of disposable inner linning, outside glove, sensors, data logger, and software for data collection, calibration, and analysis.

Figure 5. Picture of DataGlove sensor mounting. Sensors are mounted in a non-orthogonal plane to mimimize crosstalk and accurately record wrist motions.

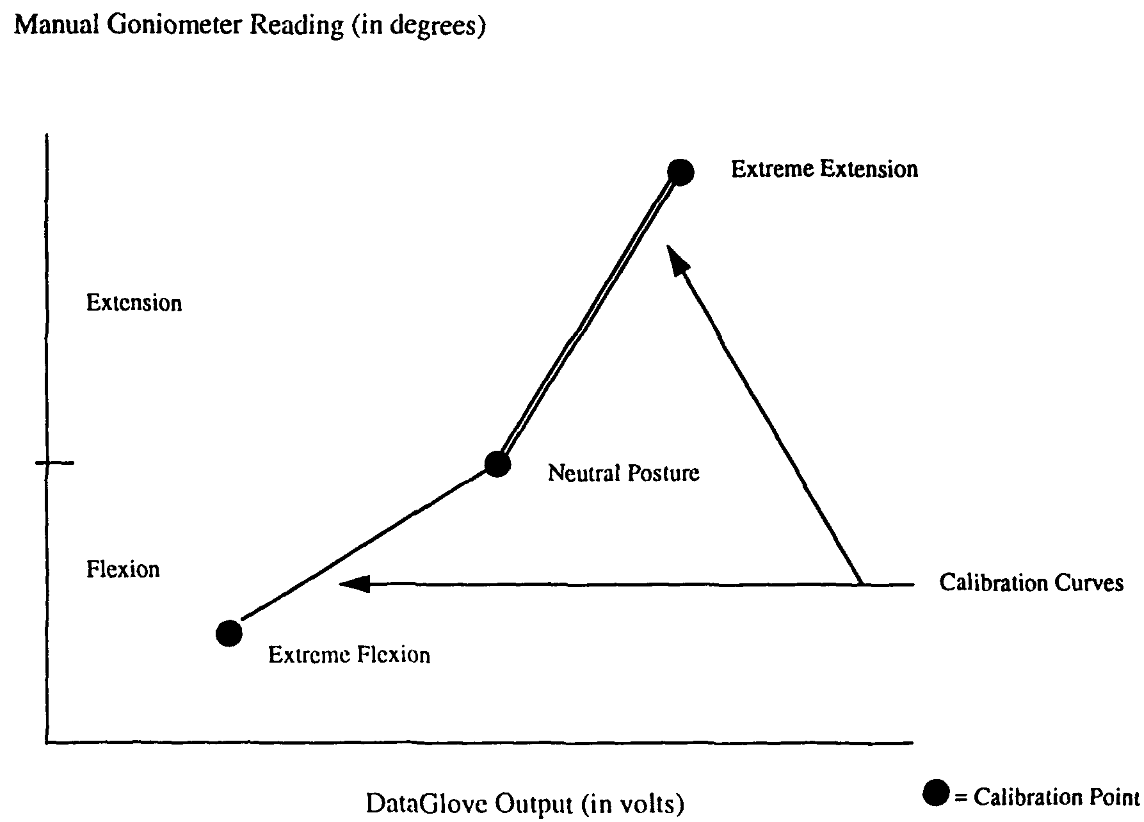


Figure 6. Graph illustrating how the DataGlove used individual manual goniometer data to develop individual calibration curves. In this figure, manual goniometer measurements (in degrees) and simultaneous voltage readings from the DataGlove were taken from an individual at extreme extension, extreme flexion, and neutral posture. From this data, two separate slopes were developed for wrist flexion and wrist extension. These slopes were used for subsequent conversion of the DataGlove output in volts to wrist flexion/extension deviation in degrees. A similar procedure was used for wrist ulnar/radial deviation.

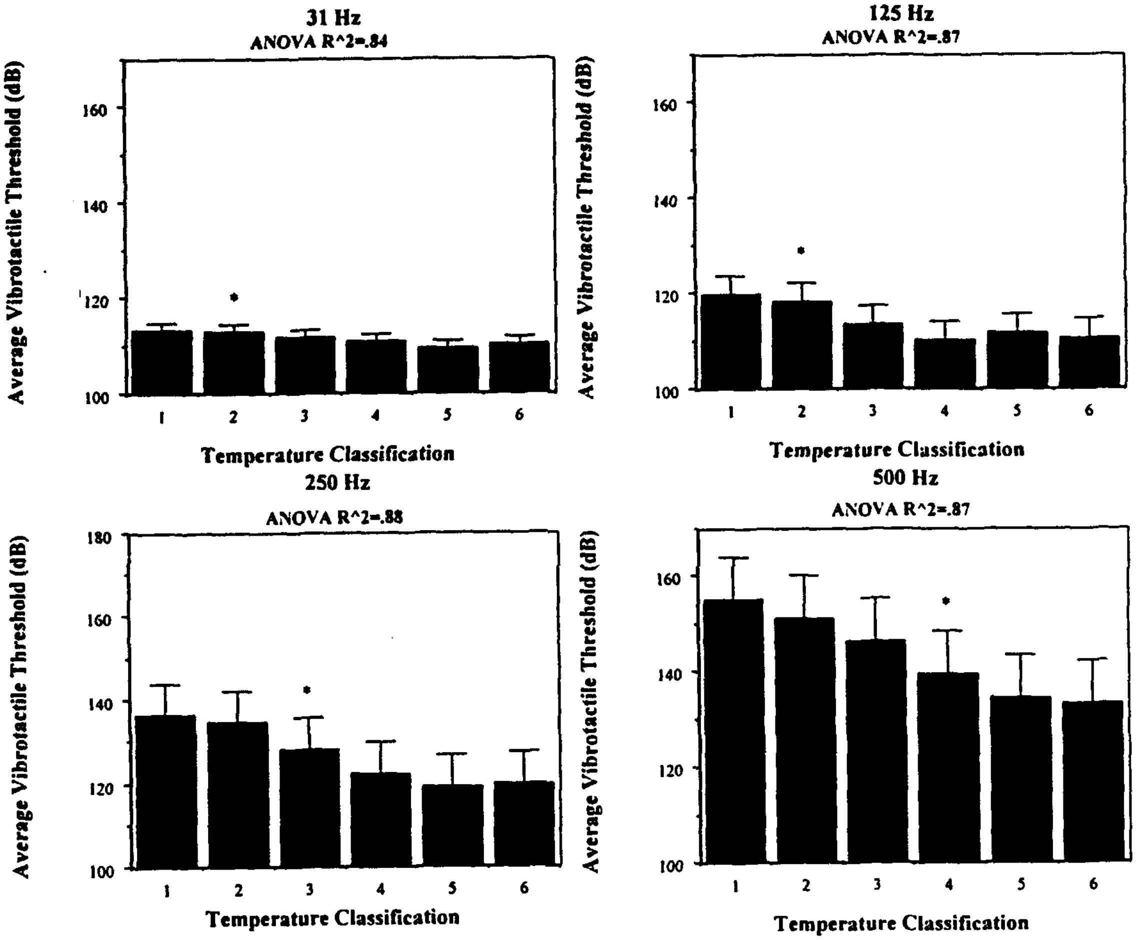


Figure 7. Graphs illustrating the relationship of vibrotactile threshold and fingertip skin temperature at four different frequencies (31.5, 125, 250, 500 Hz). Classifications: 1: 17-20 °C, 2: 20-23 °C, 3: 23-26 °C, 4: 26-29 °C, 5: 29-32 °C, 6: 32-35 °C. * represents the first temperature classification below 6 at which the vibrotactile threshold was significantly different from temperature classification 6. From the graphs, it can be seen that temperature effects are frequency dependent and greatest at the highest frequencies. A minimum fingertip skin temperature of 29° C was selected based on the 500 Hz results.

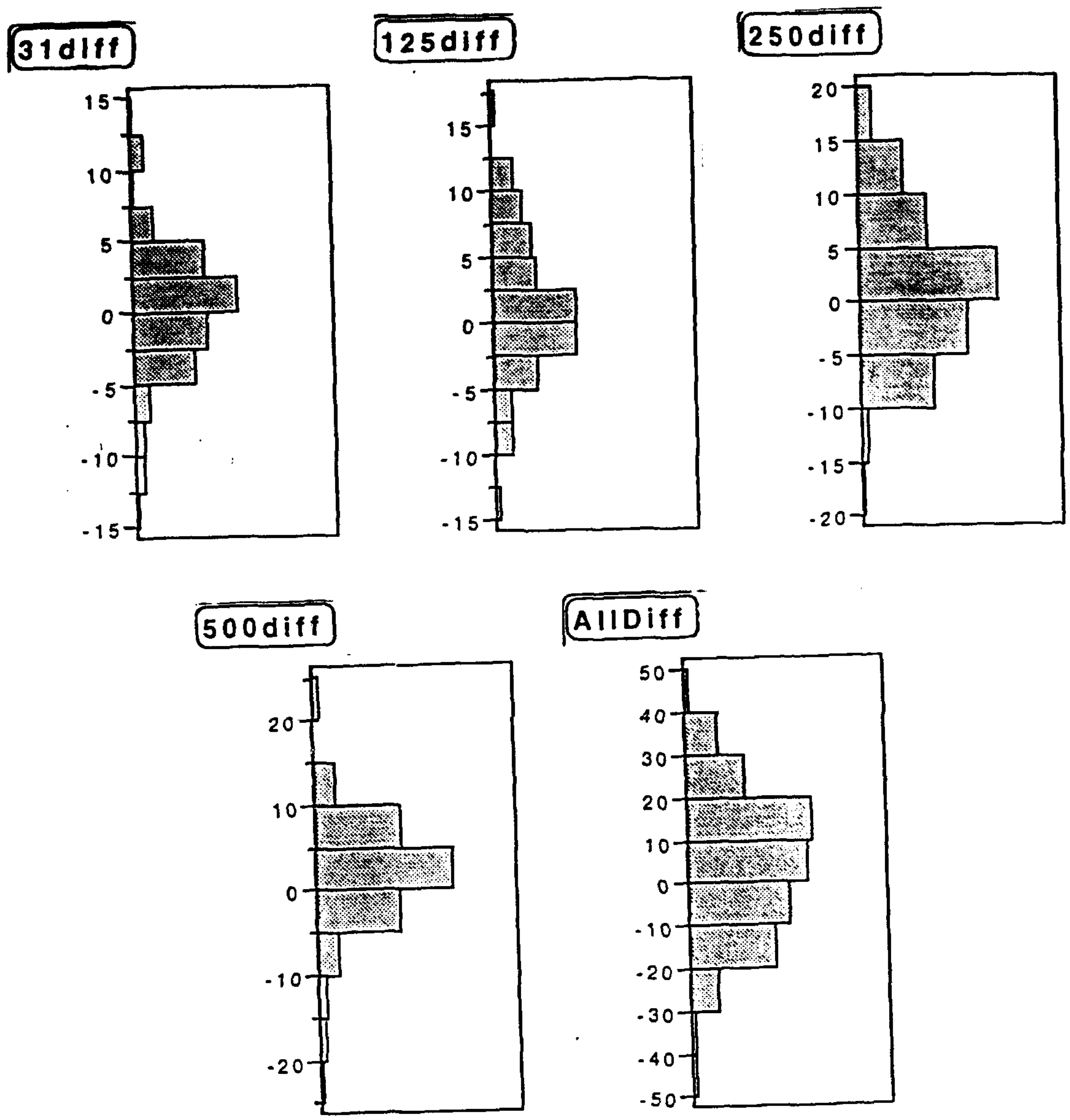


Figure 8. CVS Histograms for One Day study. CVSs were distributed normally. At the highest frequencies (125, 250, 500 Hz), the CVS across all subjects was positive and significantly different from zero. A positive difference was indicative of increased vibrotactile sensitivity over a shift.

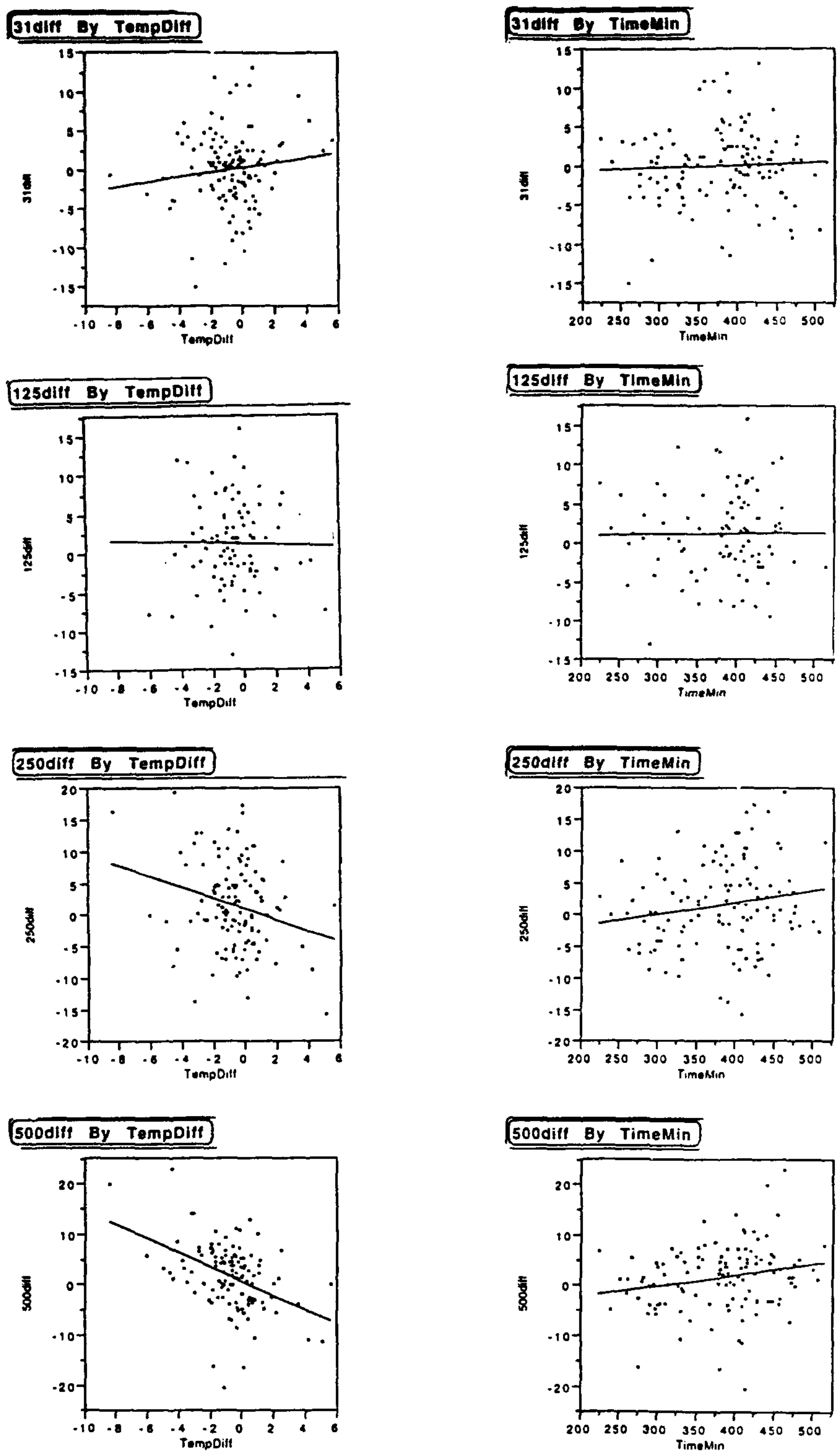


Figure 9. Graphs of CVS (31diff, 125diff, etc.) versus crosshift fingertip temperature (TempDiff) and exposure duration (Timemin) at the four tested frequencies.

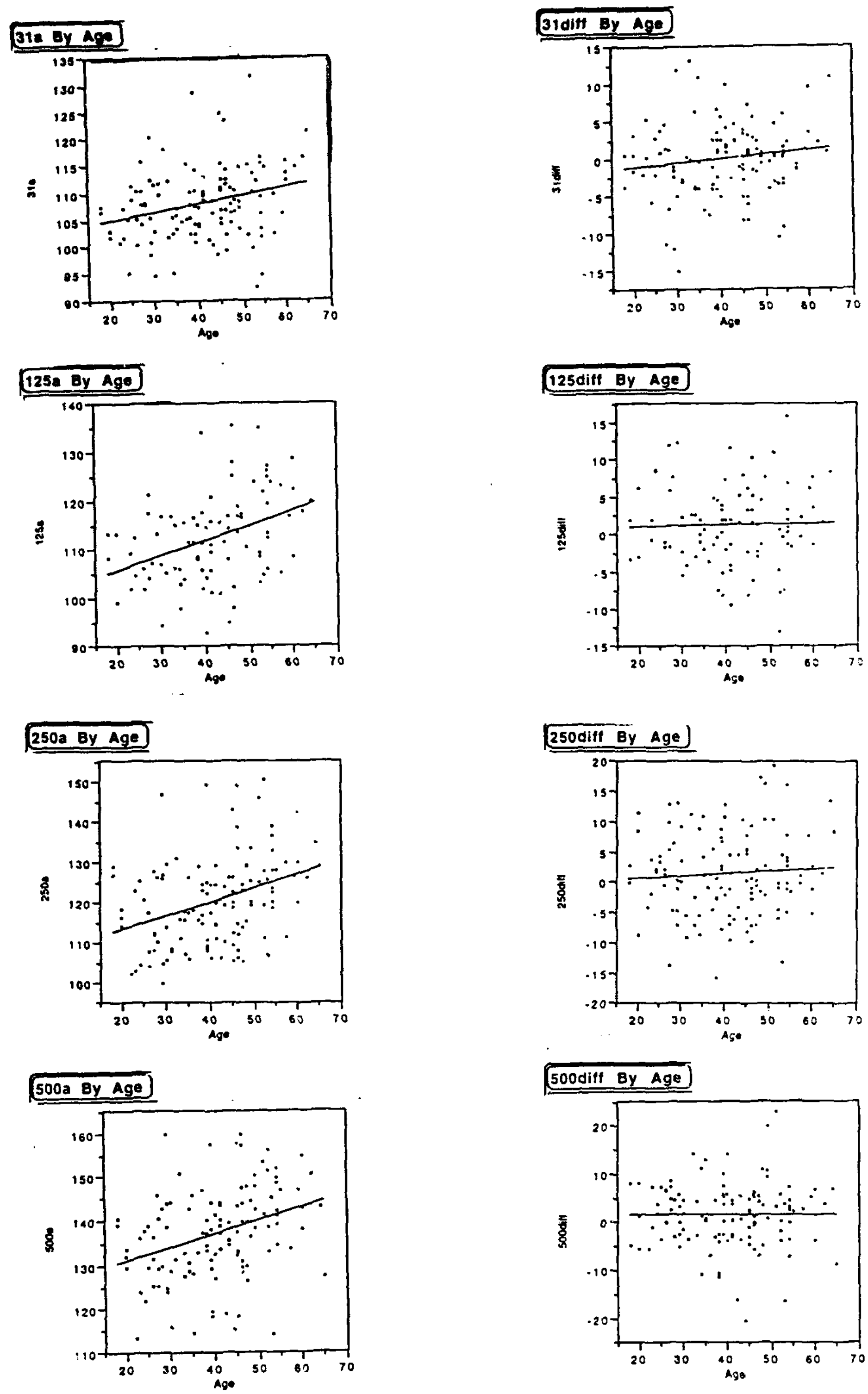


Figure 10. Graphs of morning vibrotactile threshold (31a, 125a, etc.) and CVS (31diff, 125diff, etc.) versus age at the four test frequencies.

Figure 11. Picture of typical commissary checkout stand.

McClellan AFB Workplace Task Summary

Name: ______________________________

Shop Name: ________________________

Office Symbol: _____________________

Date: _______________

Please list all tasks and the approximate time taken to perform them during the day. <u>Do not include breaks</u>.

Example:

Task	Time (Minutes)
1. Drilling	240
2. Riveting	120
3. Bucking Bar	120

TASK	TIME (Minutes)
1.	
2.	
3.	
4.	
5.	
6.	
7.	
8.	
9.	
10.	
11.	
12.	
13.	
14.	
15.	

Additional Comments:

Figure 12. Task analysis sheet used in Two Day study. This sheet was designed to provide generic information about tasks performed by workers throughout the day.

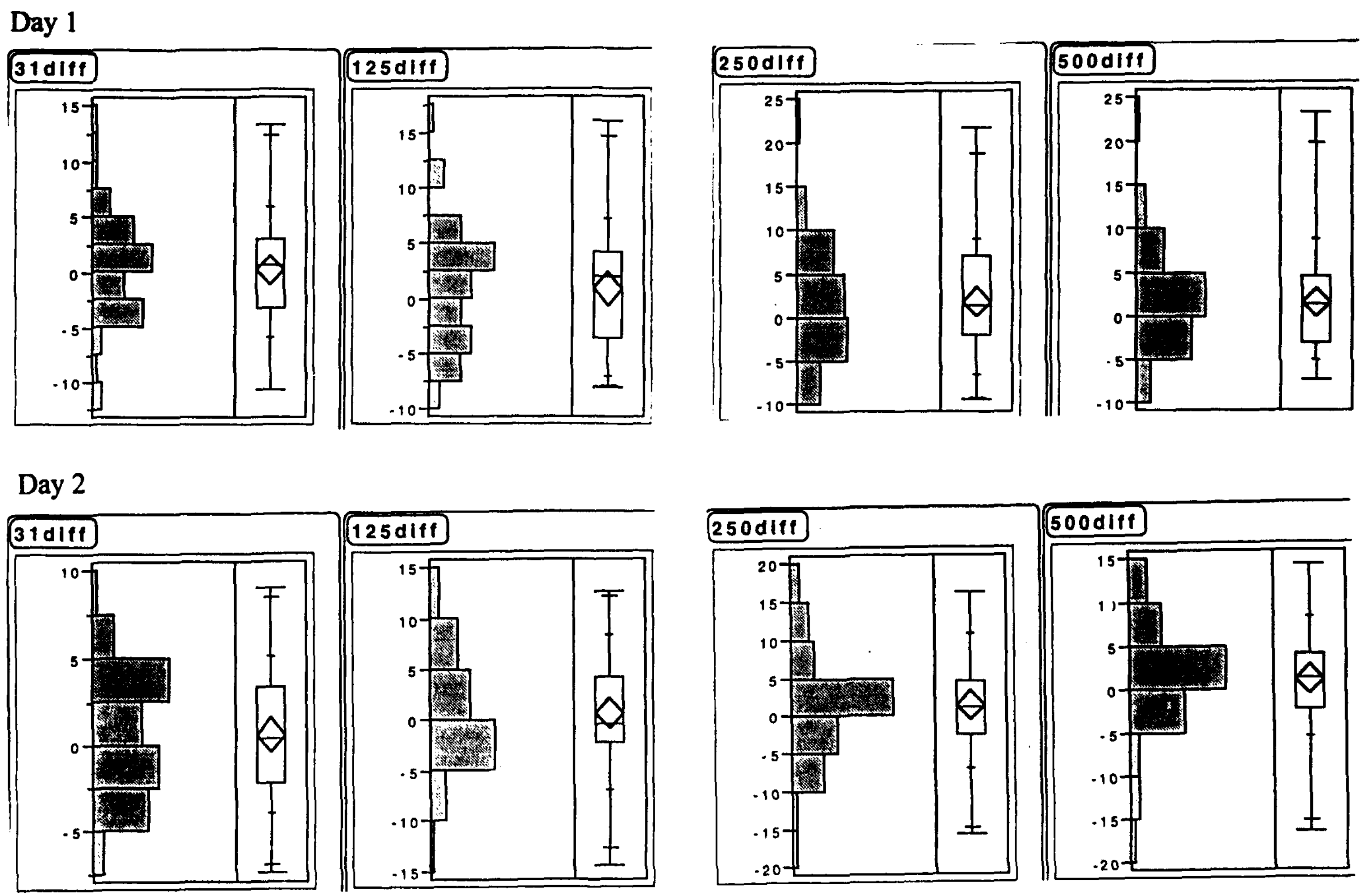
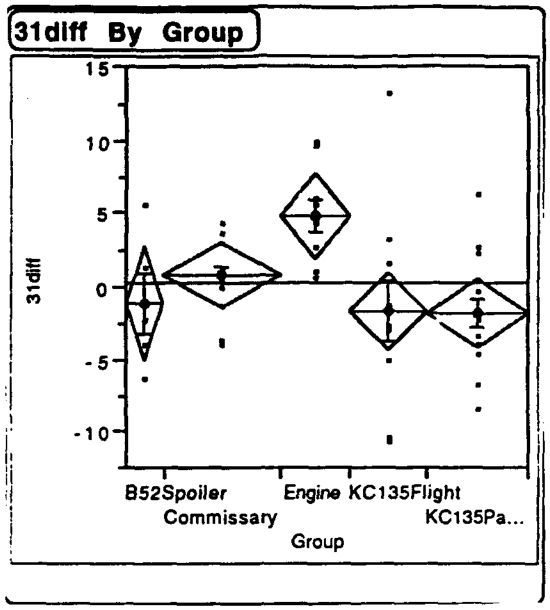


Figure 13. CVS Histograms for Two Day study. All data was normally distributed with the exception of 500 Hz, Day 2.

Day 1



Day 2

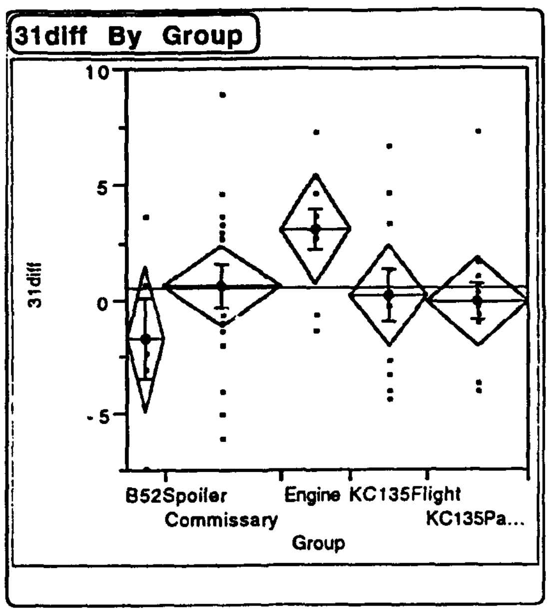


Figure 14. Graphs of CVS (31diff) versus shops (Group) for both days of testing at 31.5 Hz only. Note continuity in shop distribution of CVSs over both days of testing. No similar trend was found for the other three test frequencies.

Day 1

Day 2

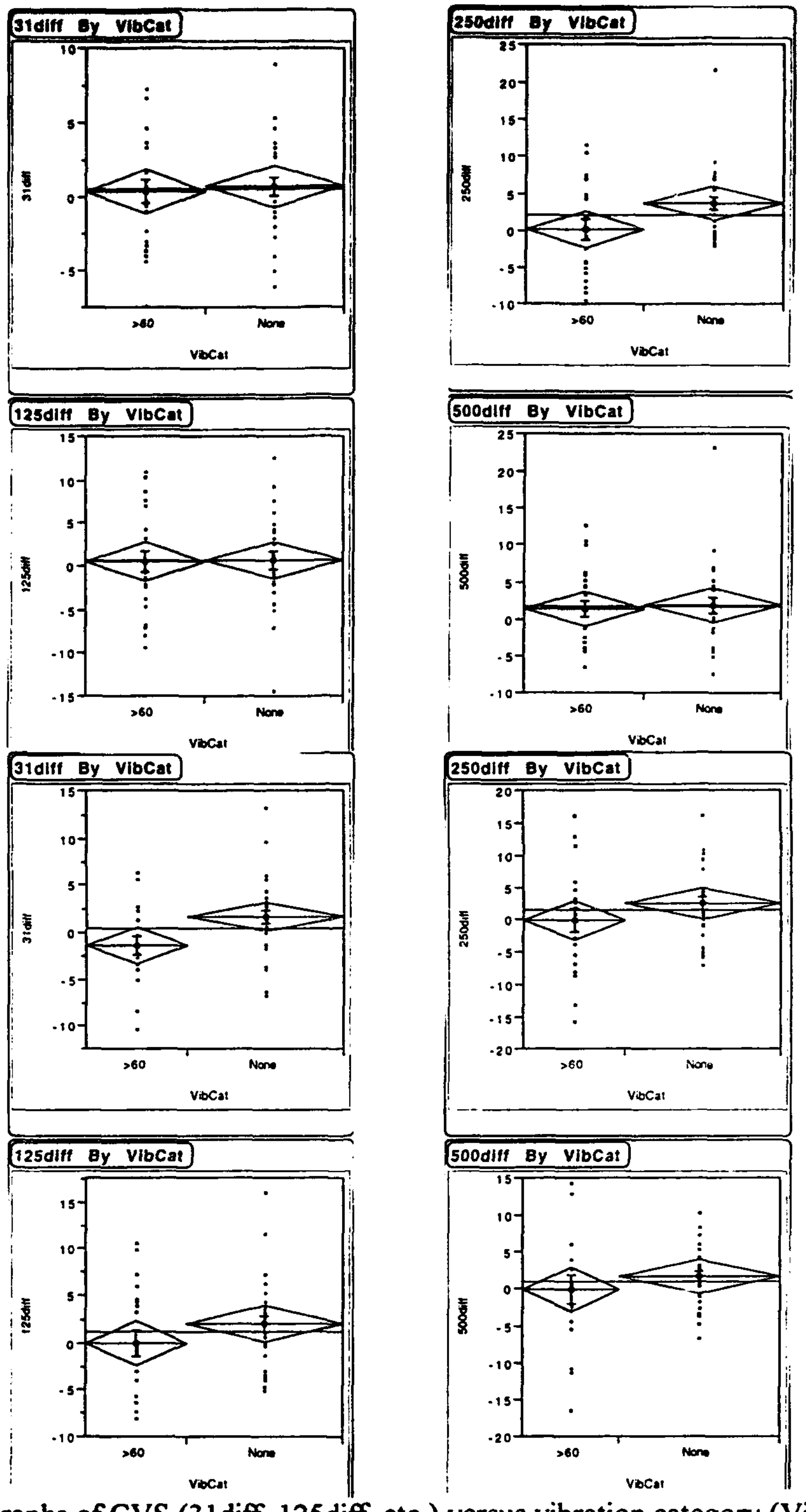


Figure 15. Graphs of CVS (31diff, 125diff, etc.) versus vibration category (VibCat) for both days of testing. Two vibration categories were used (no vibration, >60 minutes of vibration). Categories were determined based on subjects response on the task analysis sheet.

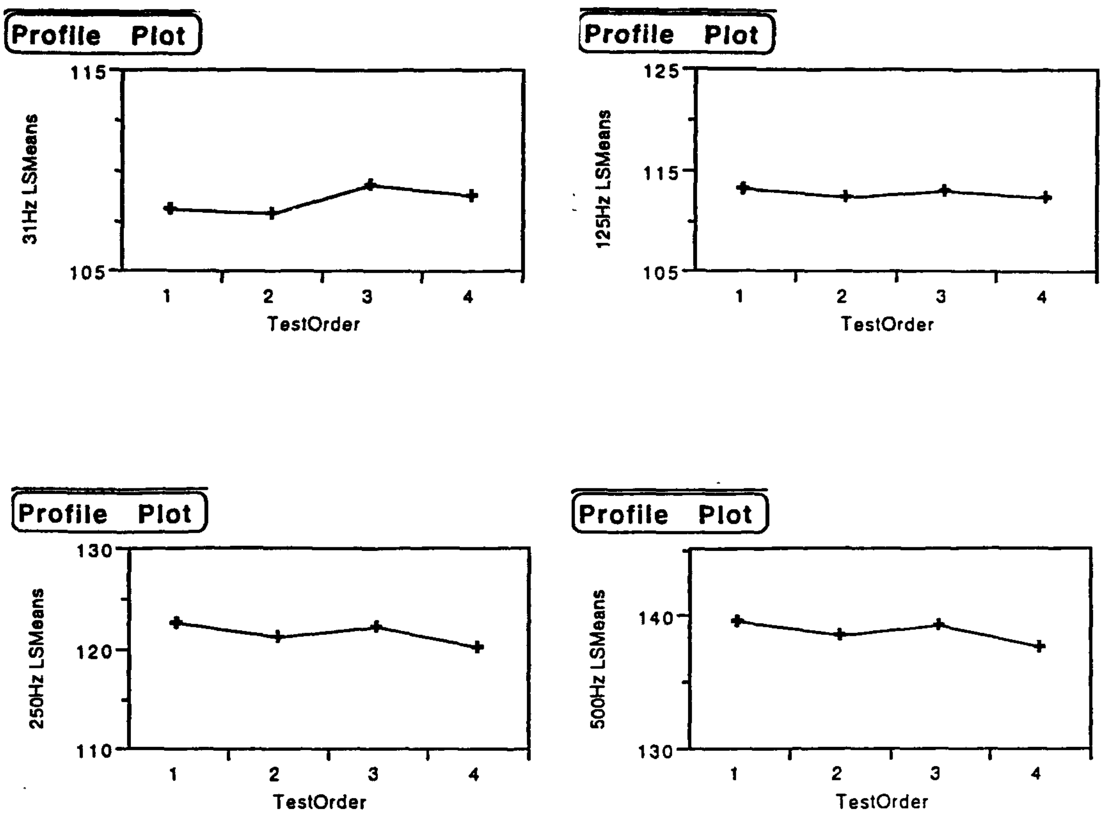
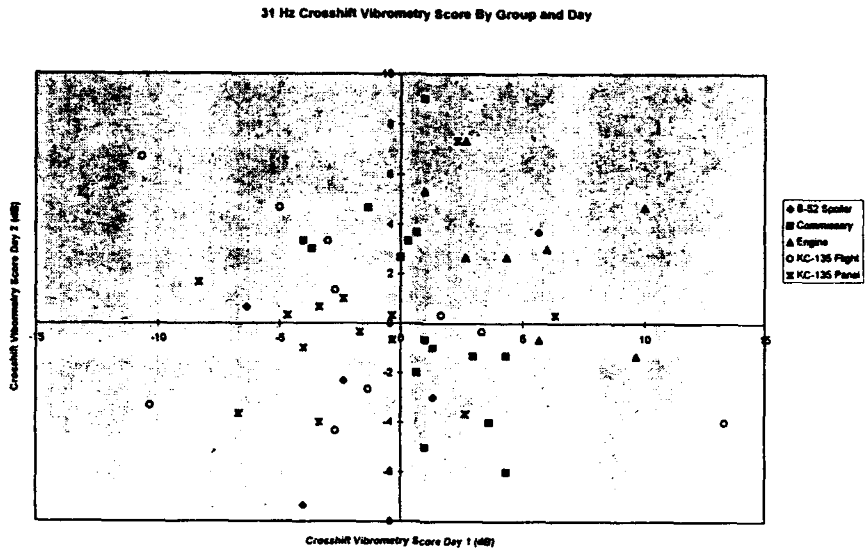


Figure 16. Graph of absolute vibrotactile thresholds (not CVS) versus test order for the four frequencies tested. Test order 1-4 corresponds to Day 1 AM, Day 1 PM, Day 2 AM, and Day 2 PM. At all frequencies, mean morning vibrotactile threshold was higher than mean afternoon vibrotactile threshold.



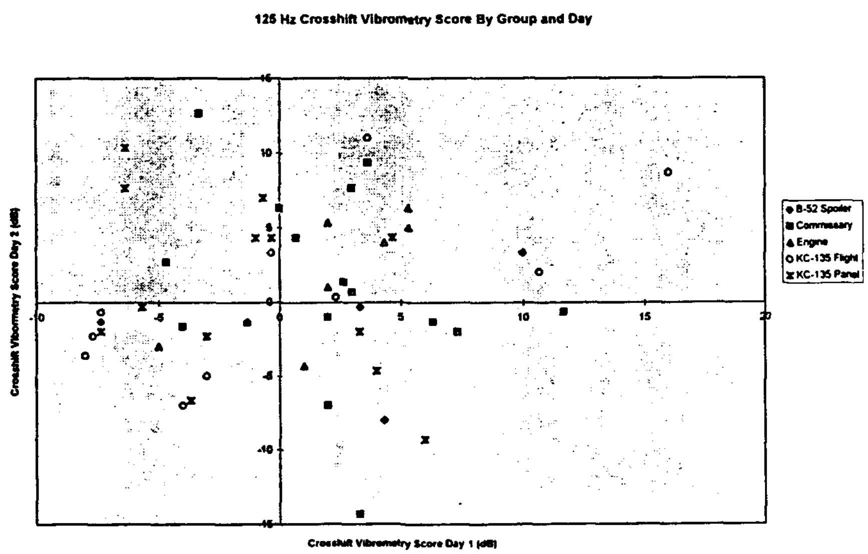
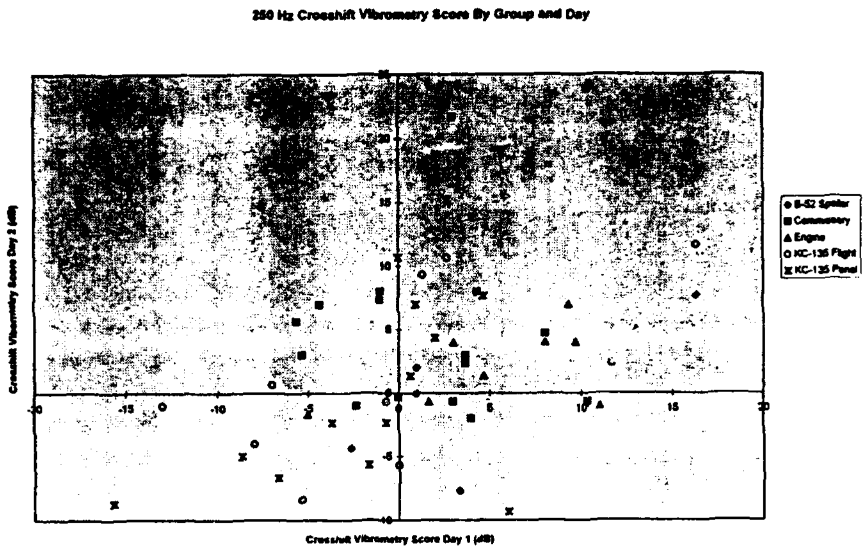


Figure 17a. Graphs comparing Day 2 CVS to Day 1 CVS for 31.5 and 125 Hz. Each shop has a distinct symbol.



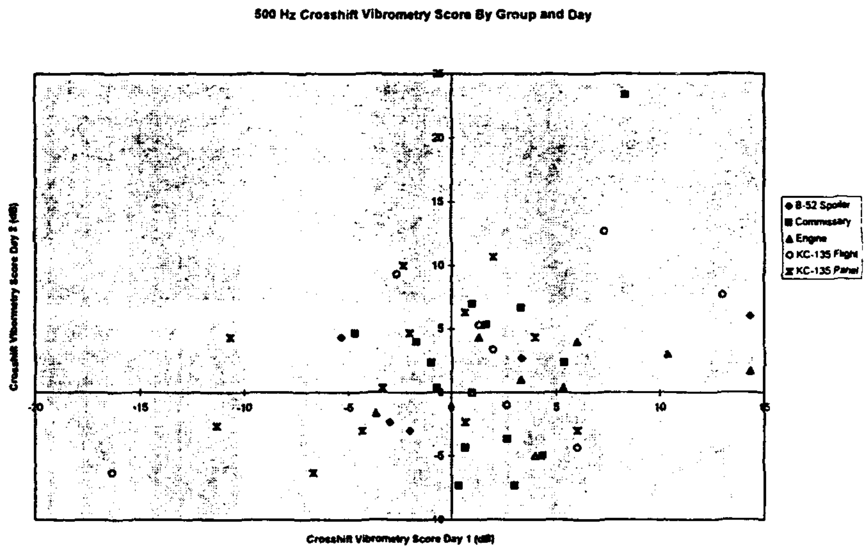
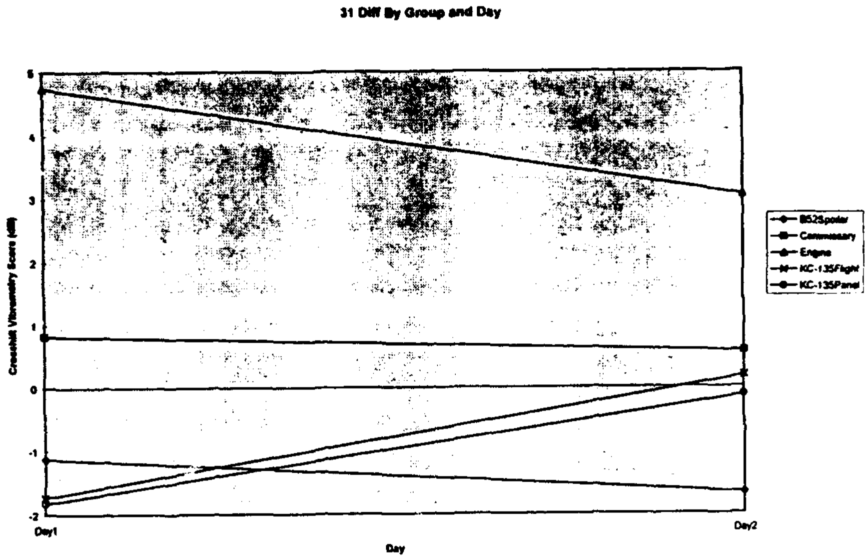


Figure 17b. Graphs comparing Day 2 CVS to Day 1 CVS for 250 and 500 Hz. Each shop has a distinct symbol.



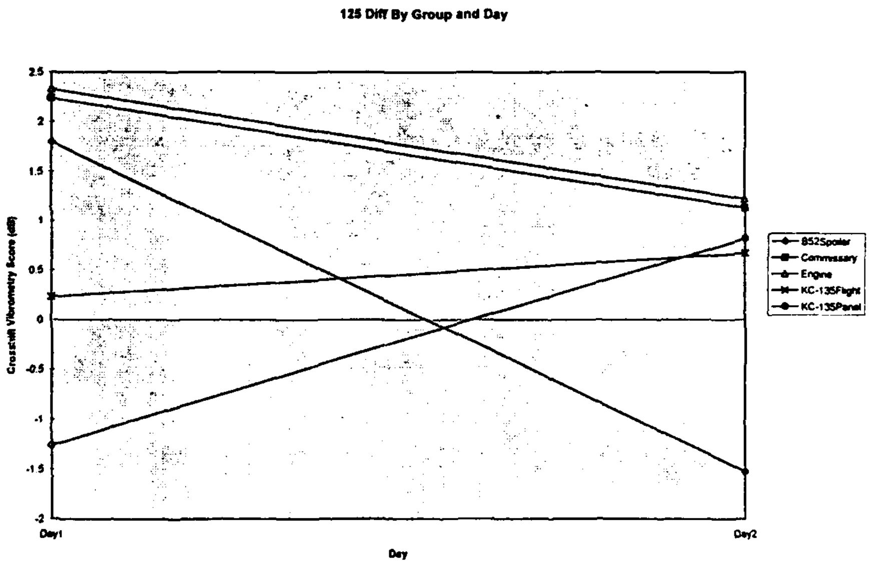
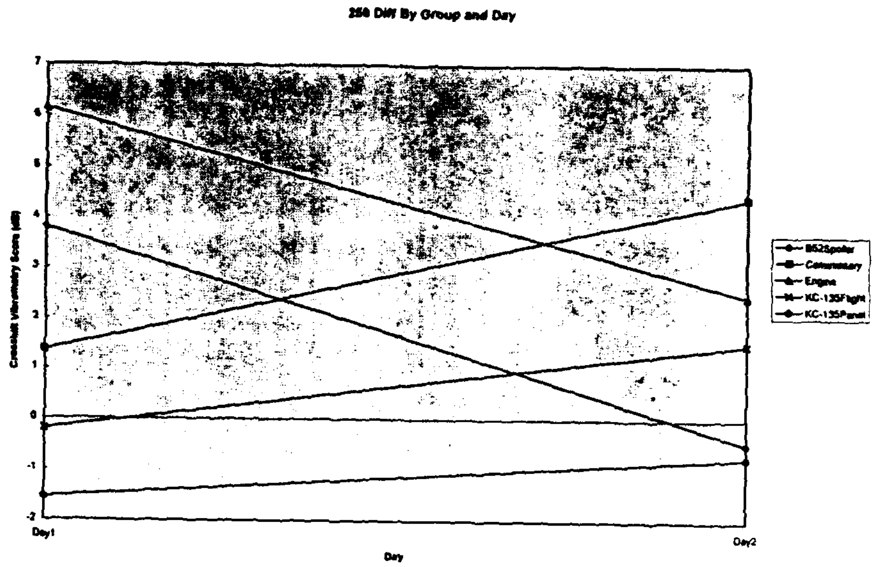


Figure 18a. Graphs of CVS versus day tested for 31.5 and 125 Hz. Mean response for each shop is shown in the graph. Engine shop personnel had positive mean responses across all frequencies for both days of testing. Other shops did not have a similar response.



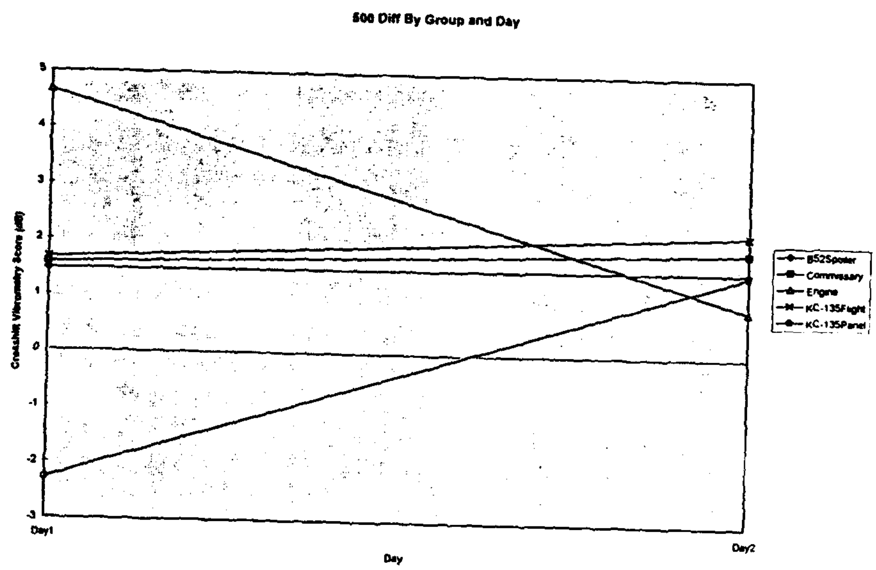


Figure 18b. Graphs of CVS versus day tested for 250 and 500 Hz. Mean response for each shop is shown in the graph. Engine shop personnel had positive mean responses across all frequencies for both days of testing. Other shops did not have a similar response.

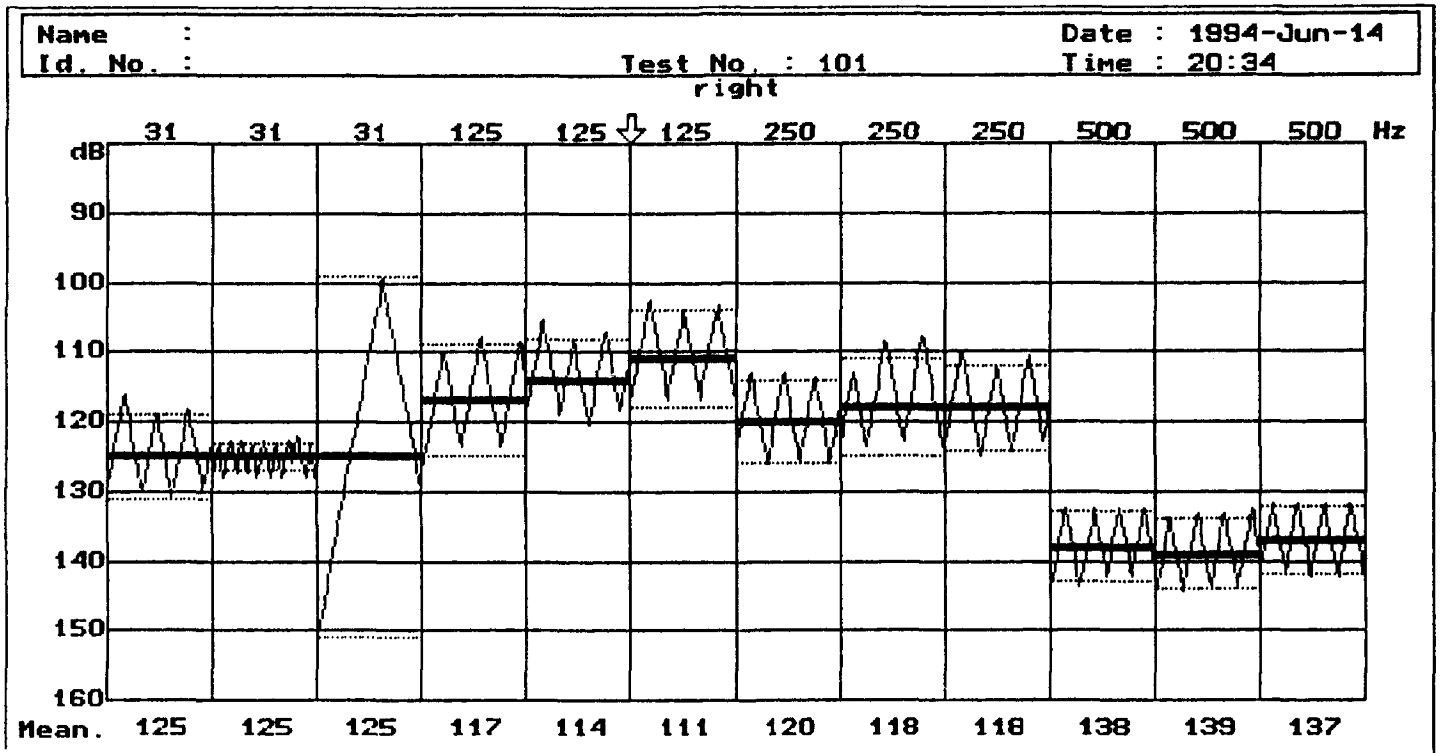


Figure 19. Simulated vibrogram illustrating how subjects can have the same vibrotactile thresholds, but widely varying response times. As can be seen in the 31.5 Hz responses, trial one is indicative of a normal response for this individual. Trial two is a fast response. In this trial, a greater number of VPTs and VDTs are used in calculation of an average vibrotactile threshold. Note also the reduced standard deviaiton for the measurement. Trial three is an example of a slow response. In this trial, only one VPT and VDT is used in calculation of an average vibrotactile threshold. Note also the large standard deviation for the measurement. The varying number of VPTs and VDTs affects the precision of average vibrotactile threshold measurement. The effect of these differences on CVSs is still unclear.

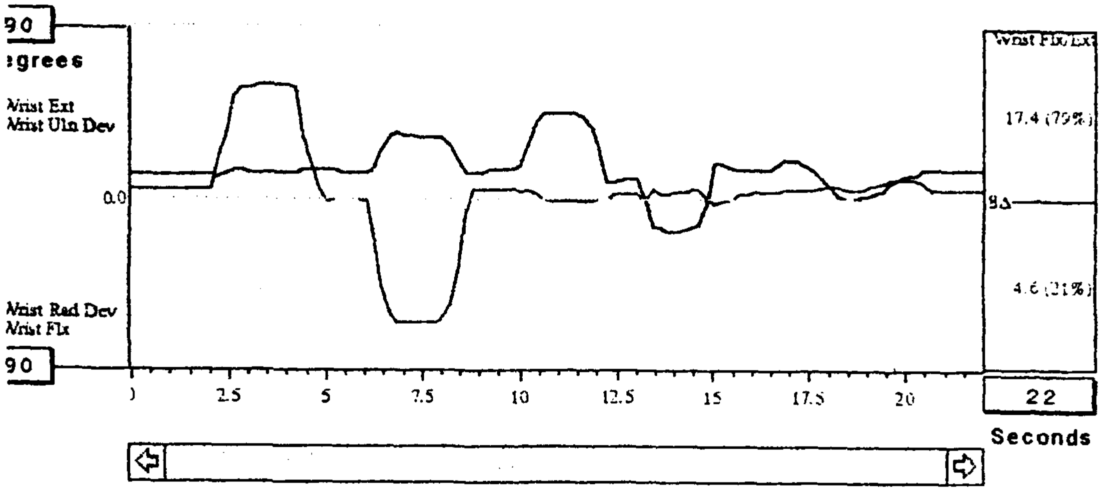


Figure 20. Plot of subject performing a series of wrist maneuvers to validate DataGlove readings prior to field data collection. Each subject started in neutral posture and was asked to move wrist to a) extreme extension, b) extreme flexion, c) extreme ulnar deviation, d) extreme radial deviation, and e) pronation/supination. Acutal postures were determined by the subject. This explains why the DataGlove output for neutral posutre was not exactly at zero for both flexion/extension and radial/ulnar deviations. It also explains, for instance, why some ulnar deviation was present during extreme flexion. As indicated in the plot, pronation and supination do cause some crosstalk in the signal.

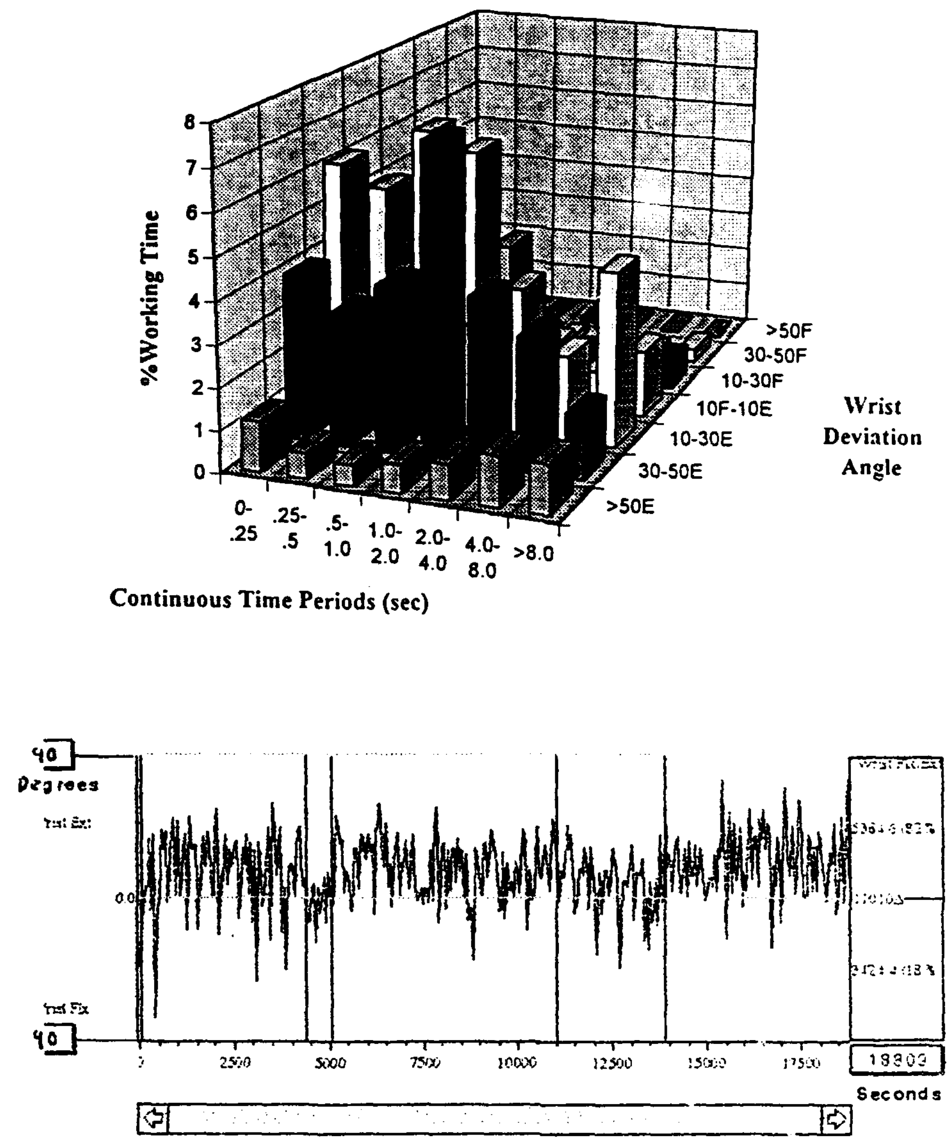


Figure 21. Comparison of raw DataGlove output to processed data using EVA plots. Comparison is made using wrist flexion/extension data. Similar plots were constructed using wrist radial/ulnar data.

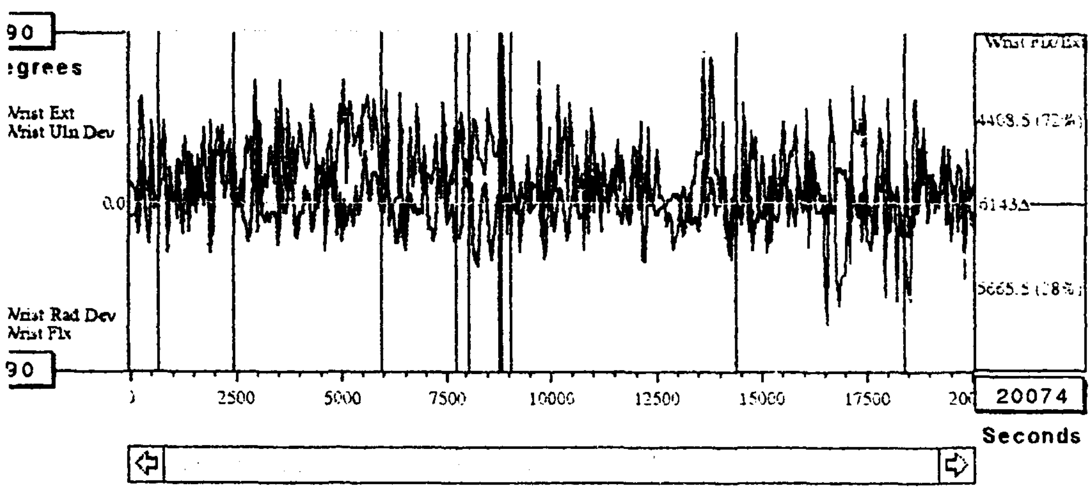


Figure 22. Plot of DataGlove data over a full day of testing. Vertical lines are timing marks used to identify tasks and breaks throughout the day.

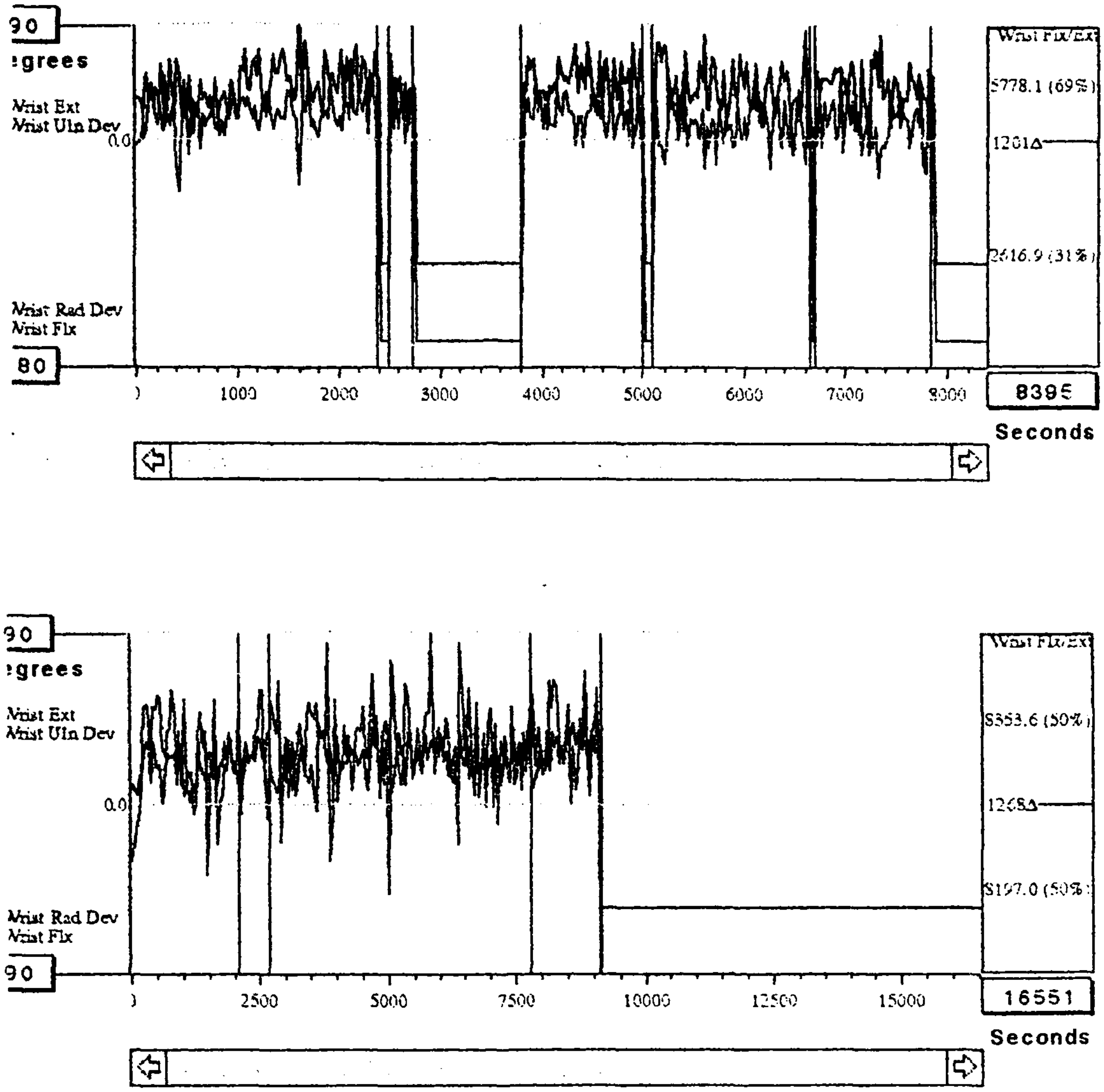


Figure 23. Examples of problems that can occur while using the DataGlove in the field. In the top plot, the subject misinterpreted the instructions and removed the testing cable while on break. The result was a flat line during breaks. In the bottom plot, the subject got the testing cable caught on a door and ripped the wires from the sensors. The result was again a flat line response.

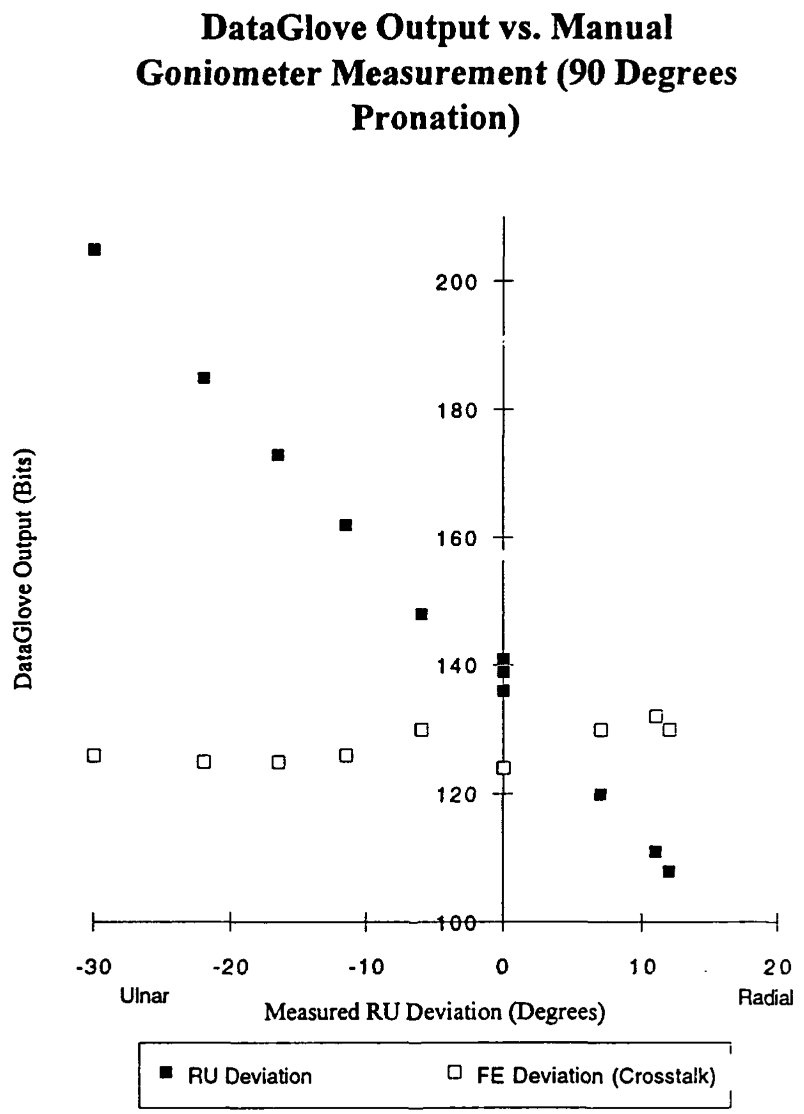
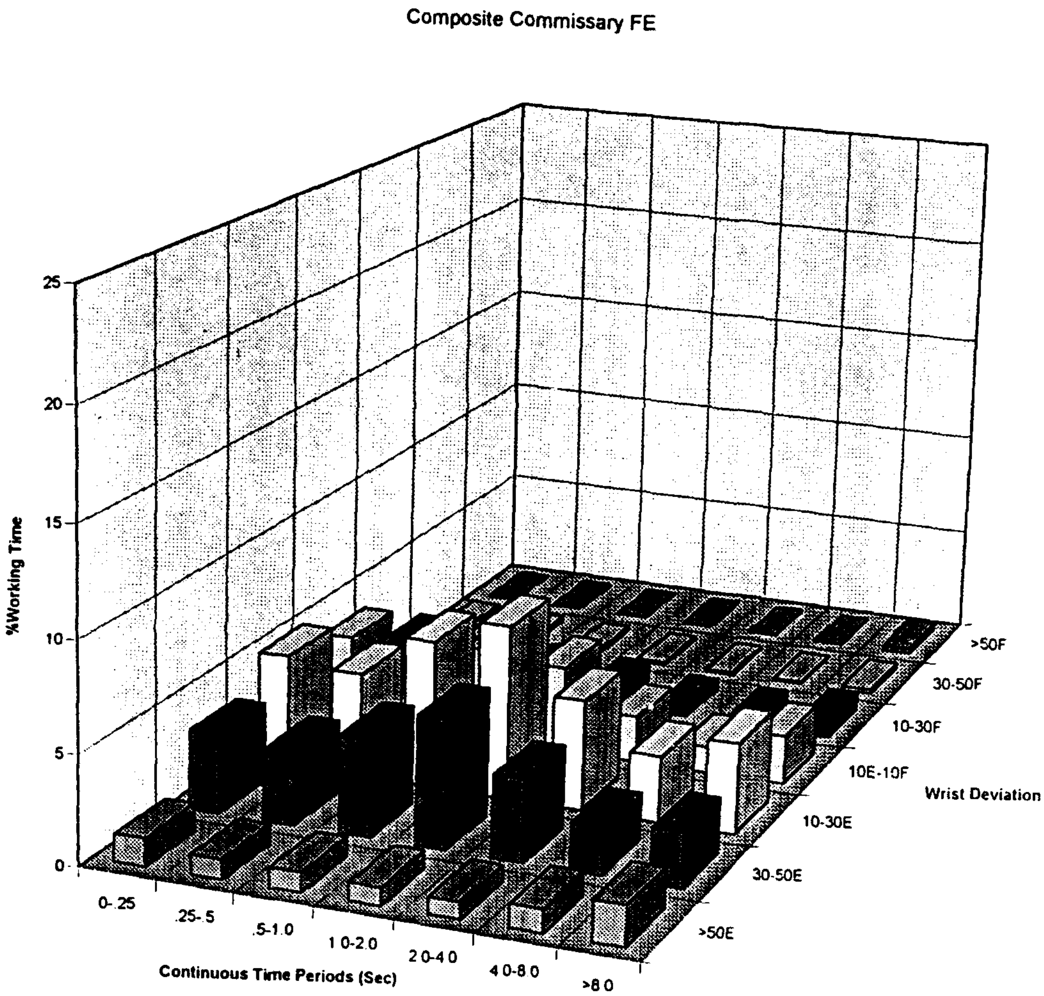


Figure 24. An example of crosstalk between channels. Crosstalk in the FE wrist deviation is minimized in the neutral posture.



Figures 25a-f. Average response EVA plots for the commissary, engine shop, and KC-135 panel shop. FE and RU wrist deviations are presented on seperate plots. Distinct differences between the commissary and the other two shops can be seen. An EVA plot for commissary FE is shown here.

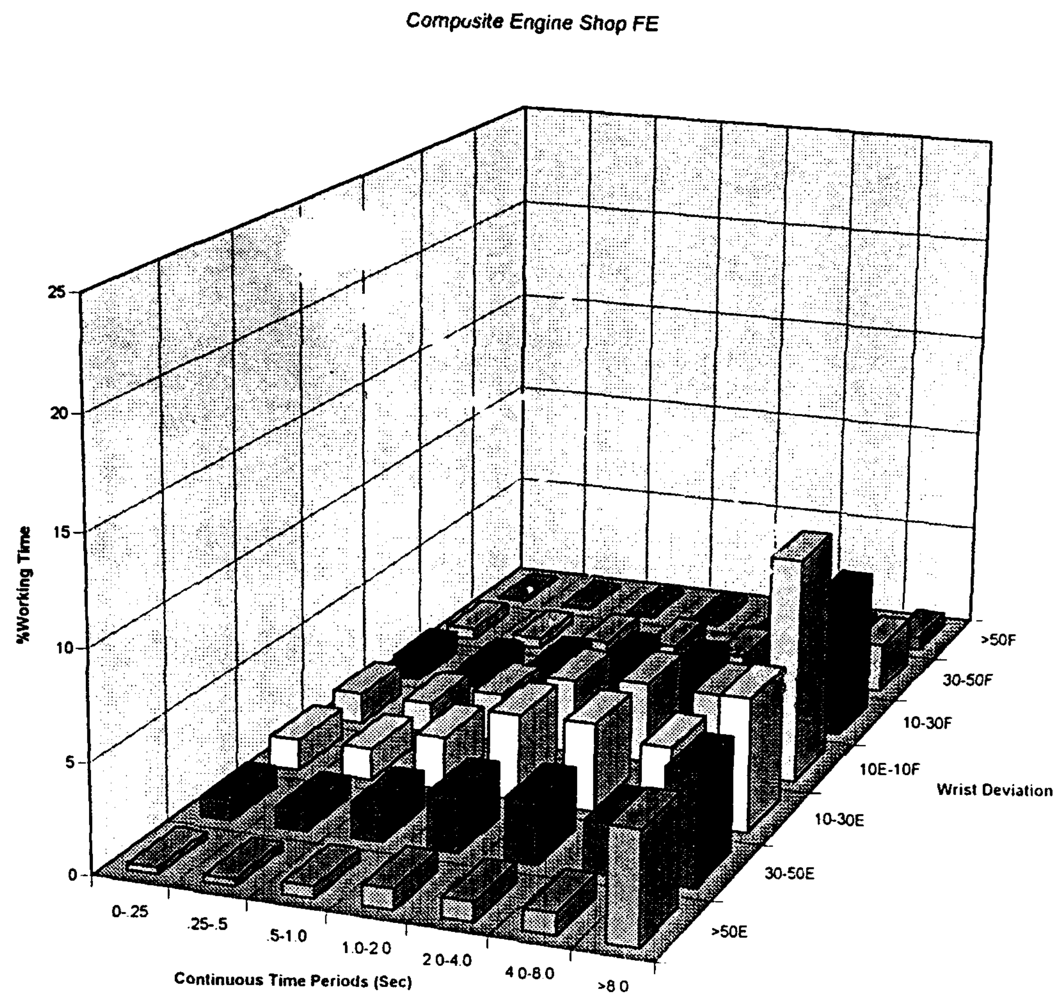


Figure 25b. Engine shop FE EVA plot.

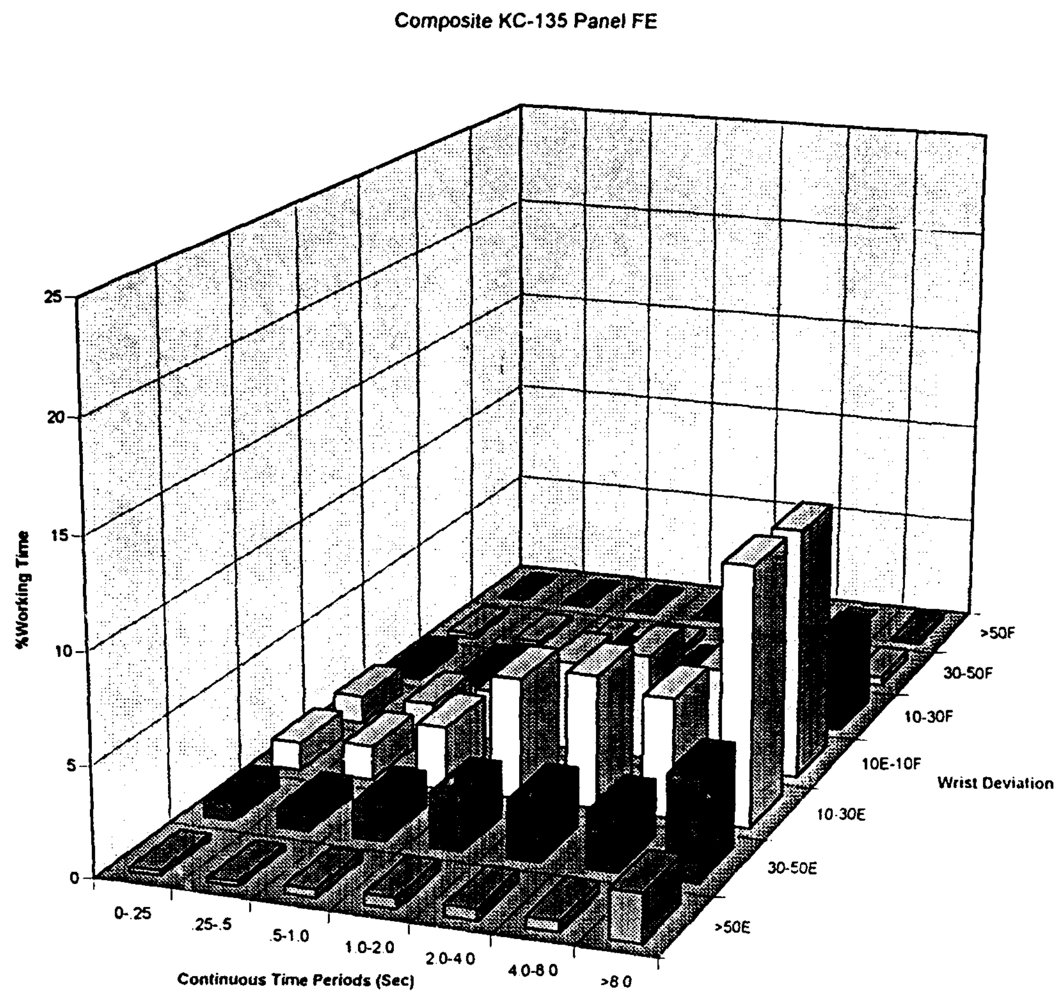


Figure 25c. KC-135 Panel shop FE EVA plot.

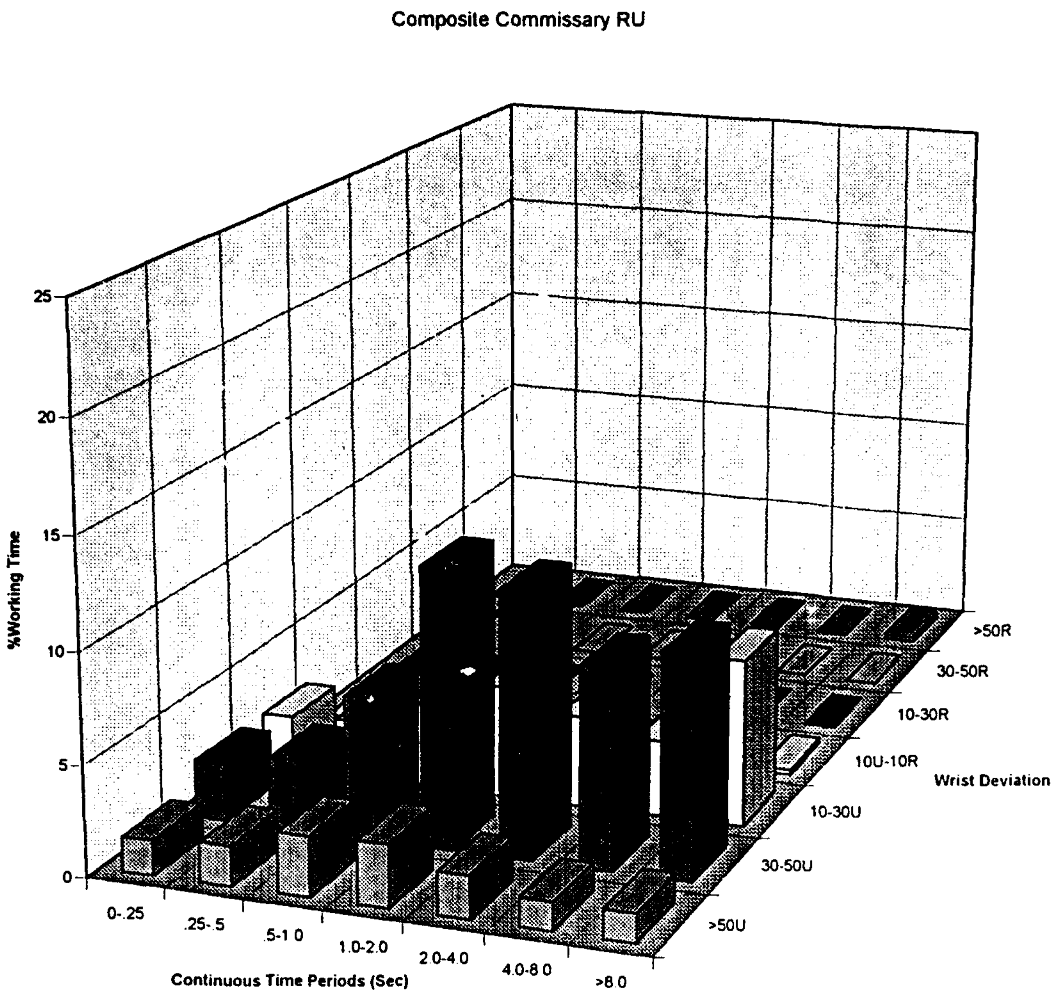


Figure 25d. Commissary RU EVA plot.

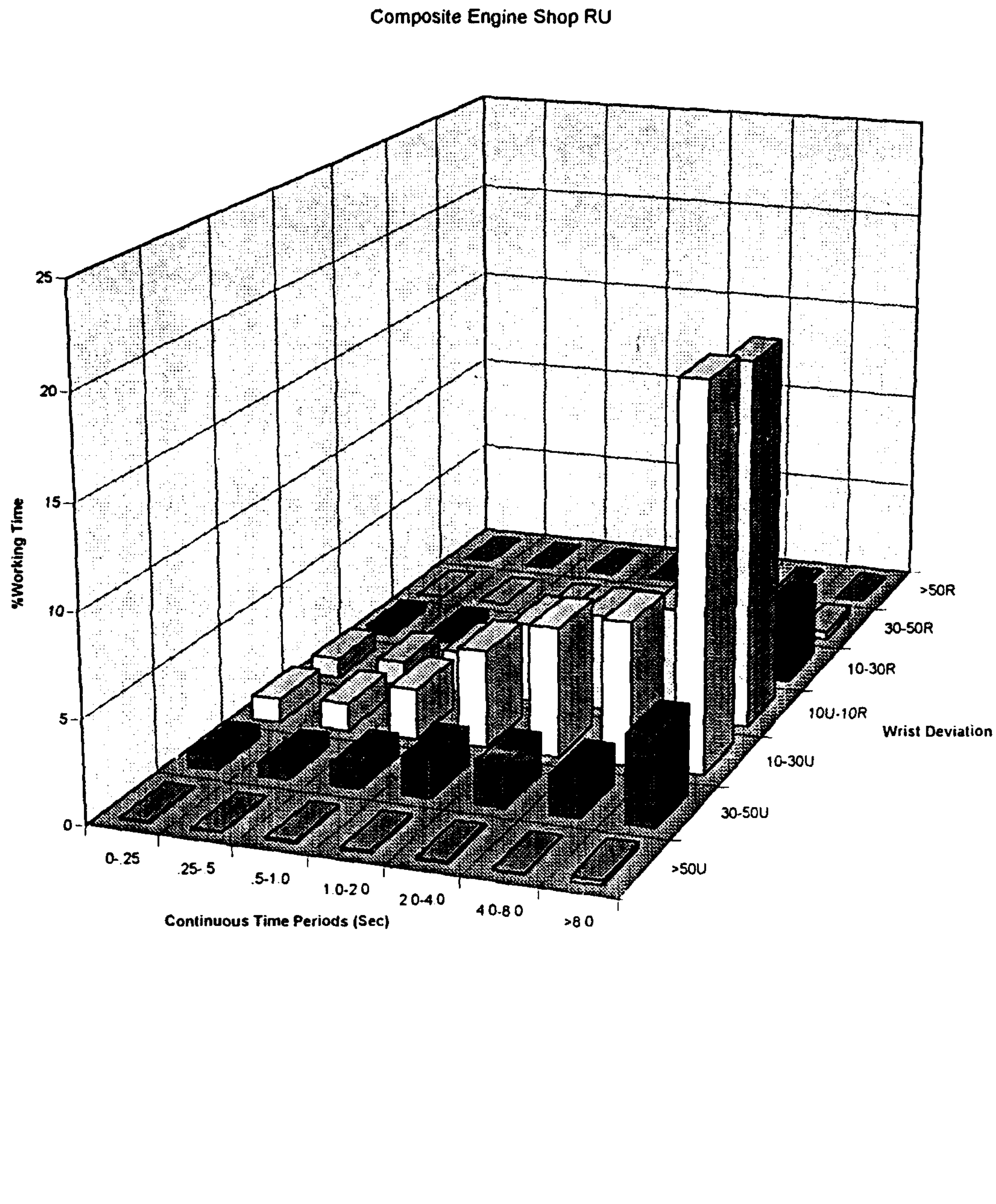


Figure 25e. Engine shop RU EVA plot.

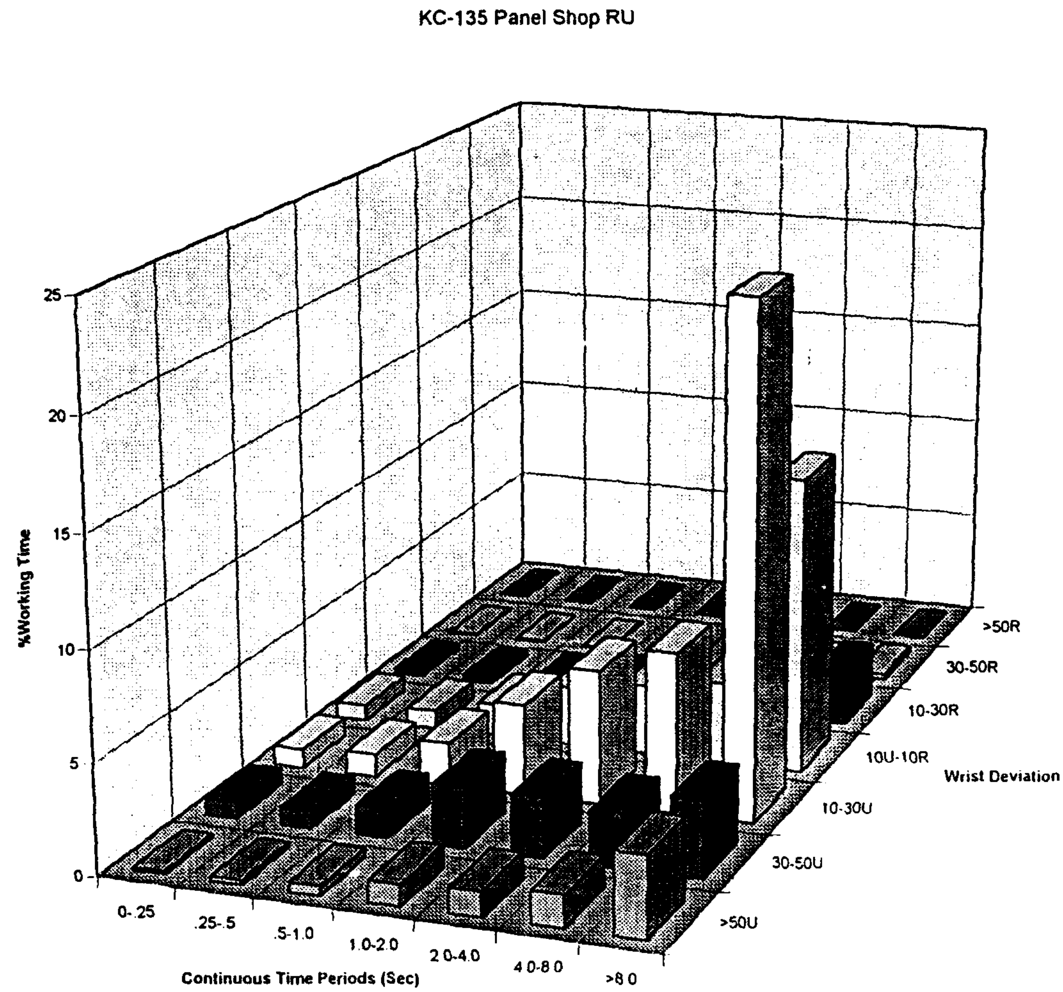


Figure 25f. KC-135 Panel shop RU EVA plot.

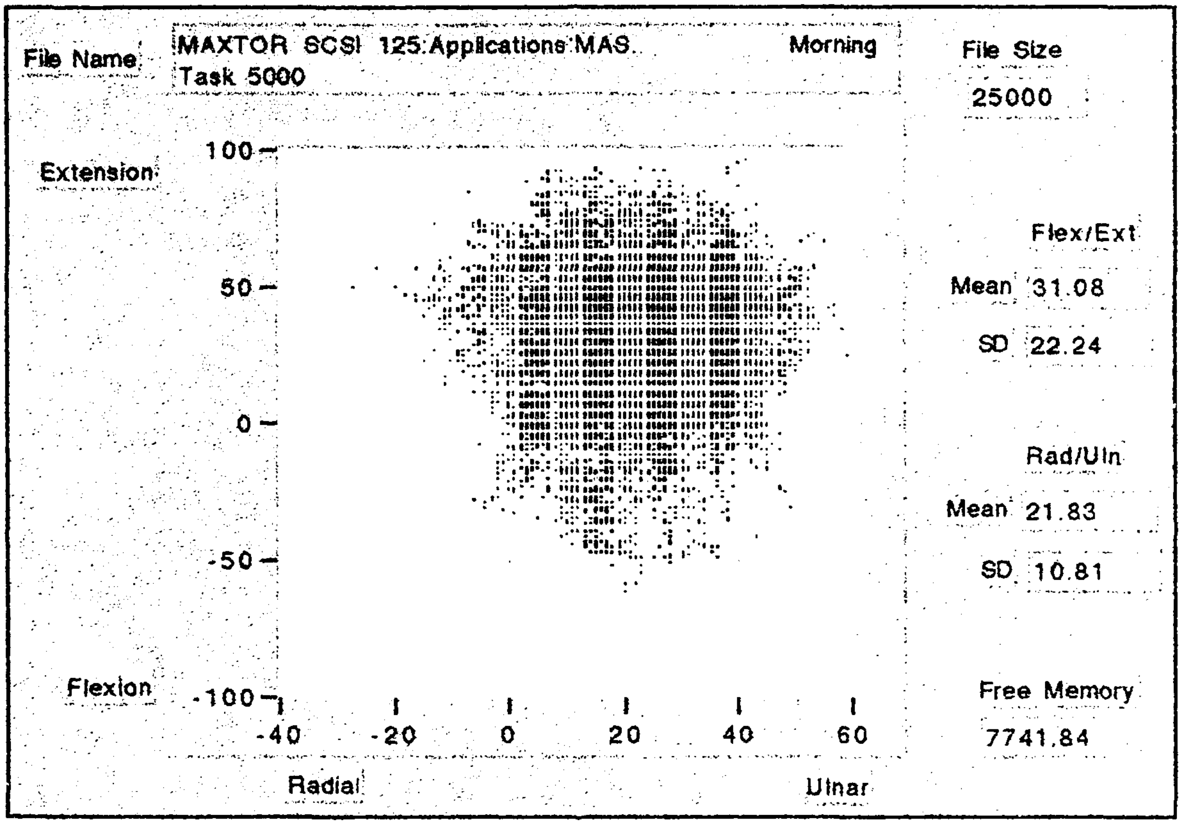


Figure 26. Example two-dimensional plot of flexion/extension and ulnar/radial wrist deviations. No bi-modal distributions were evident .

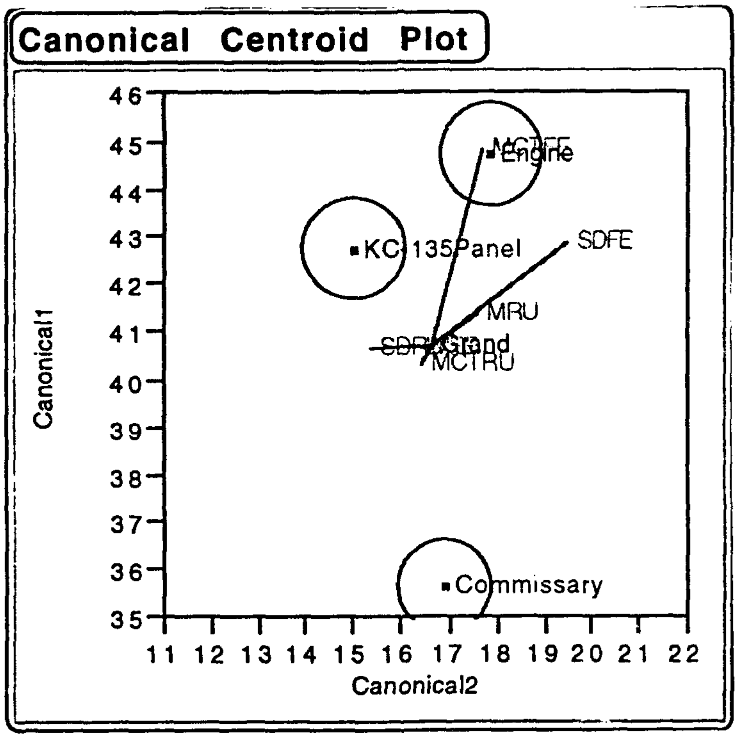


Figure 27. Discriminant function centroid plot using all collected DataGlove parameters (MCTFE, MFE, SDFE, MCTRU, MRU, SDRU). By looking at the centroid plot, distinct differences between the shops can be seen.

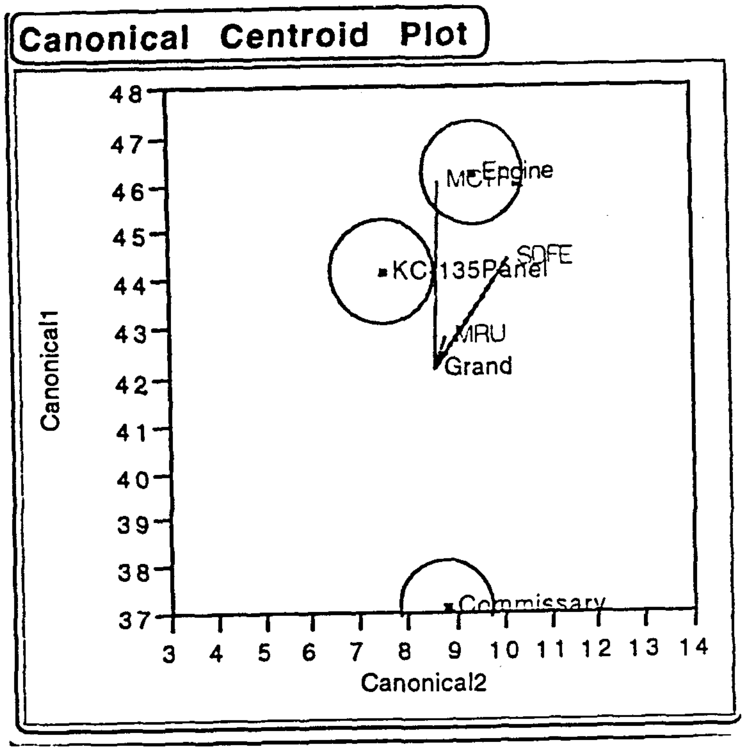


Figure 28. Discriminant function centroid plot using a subset of the collected DataGlove parameters (MCTFE, SDFE, MRU). Even with a smaller number of variables, the separation between shops remained large. By using these three variables, all subjects were classified correctly intro their respective shop.

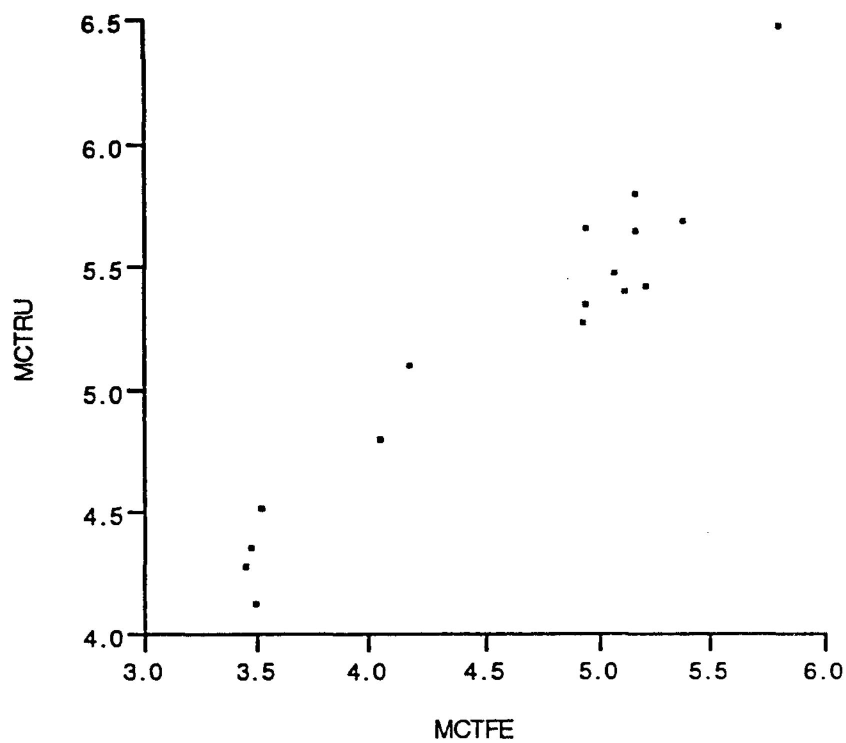


Figure 29. Graph comparing MCTFE to MCTRU. There was a strong association between MCTFE and MCTRU.

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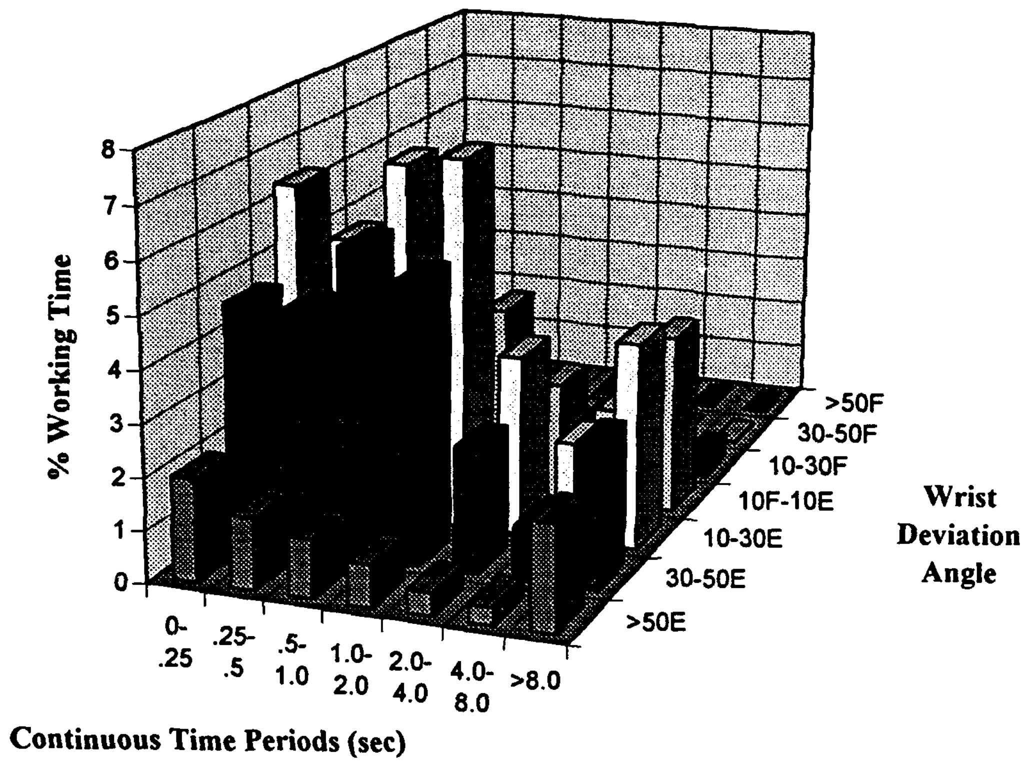
APPENDIX D: INDIVIDUAL EVA PLOTS



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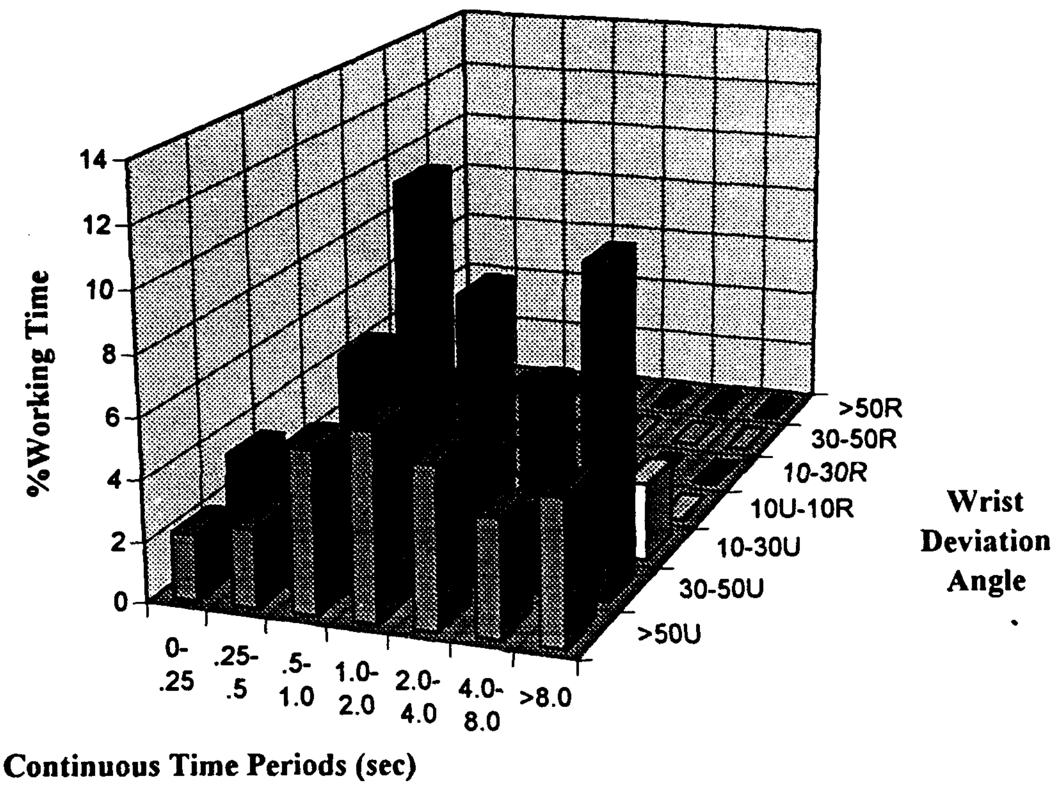

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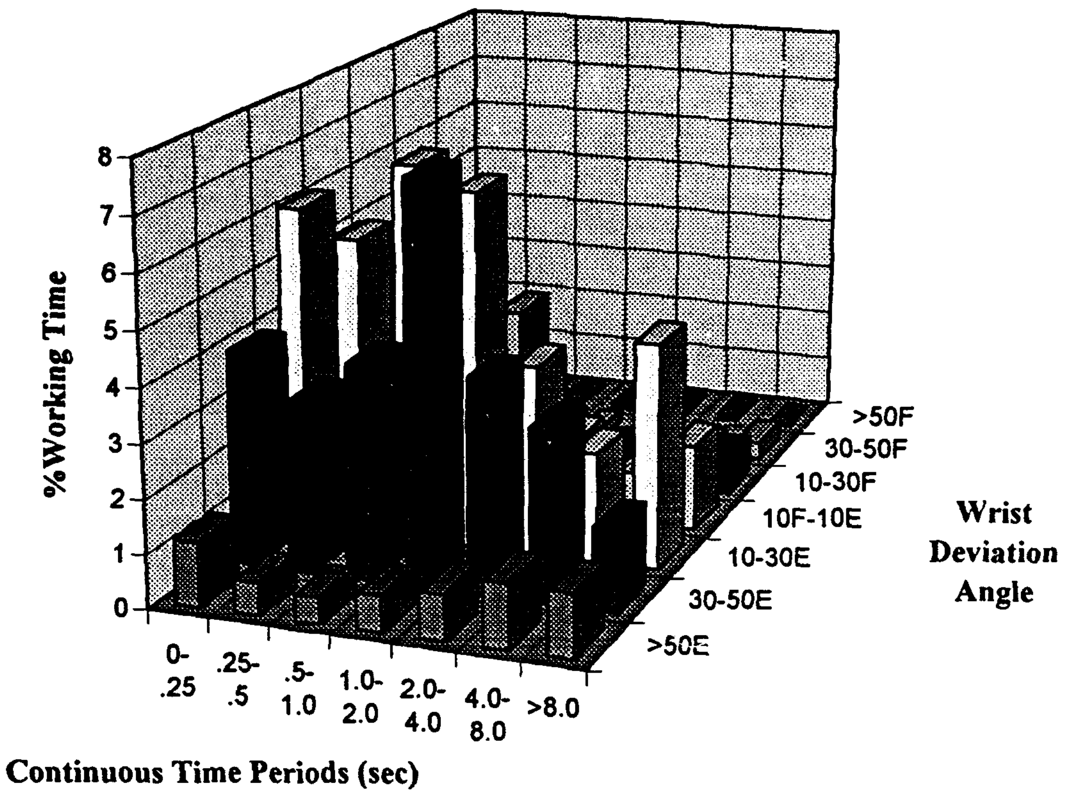

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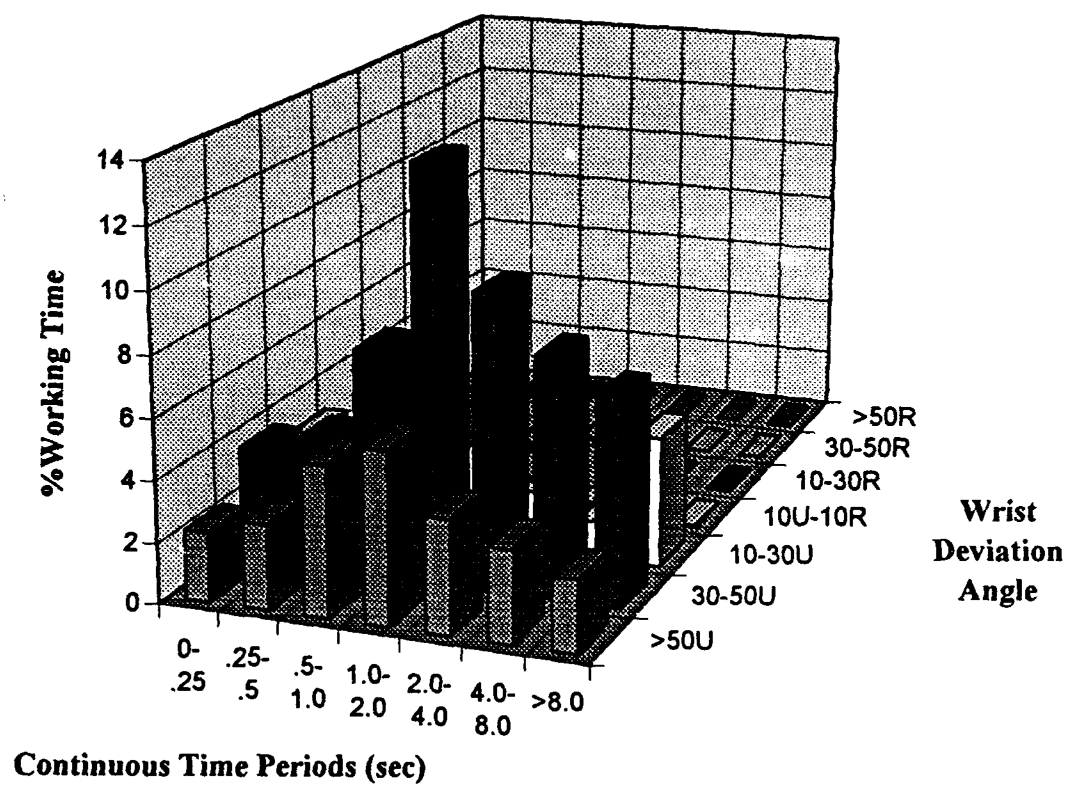

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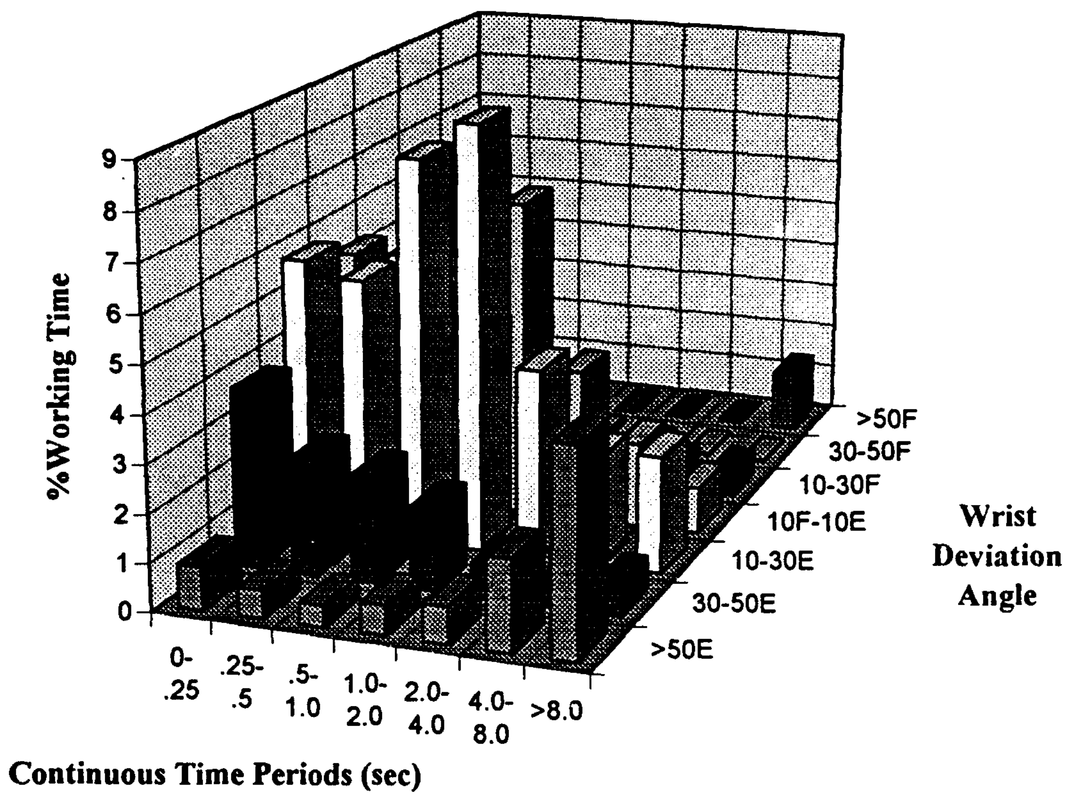

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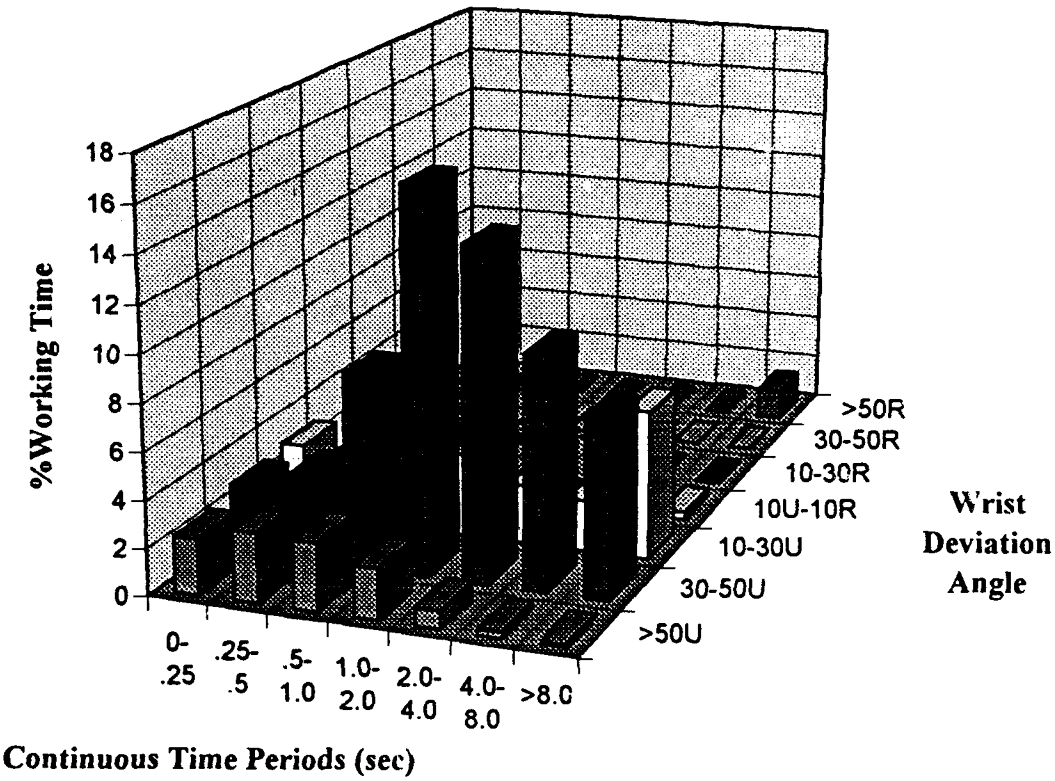

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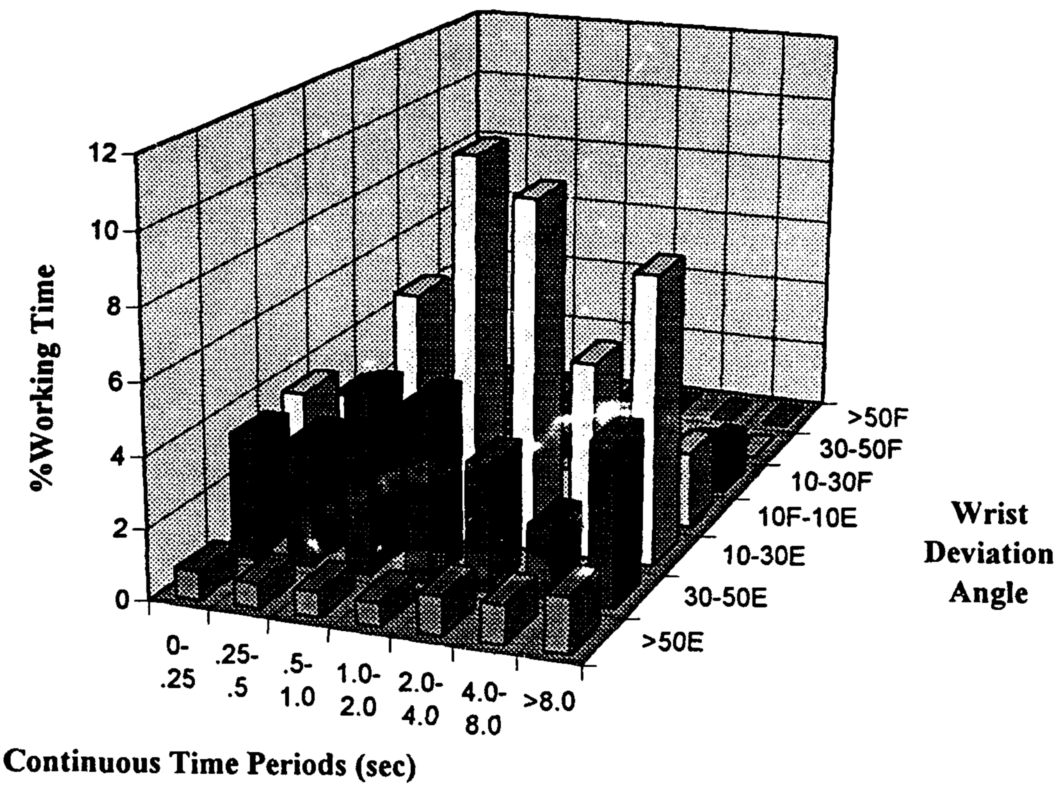

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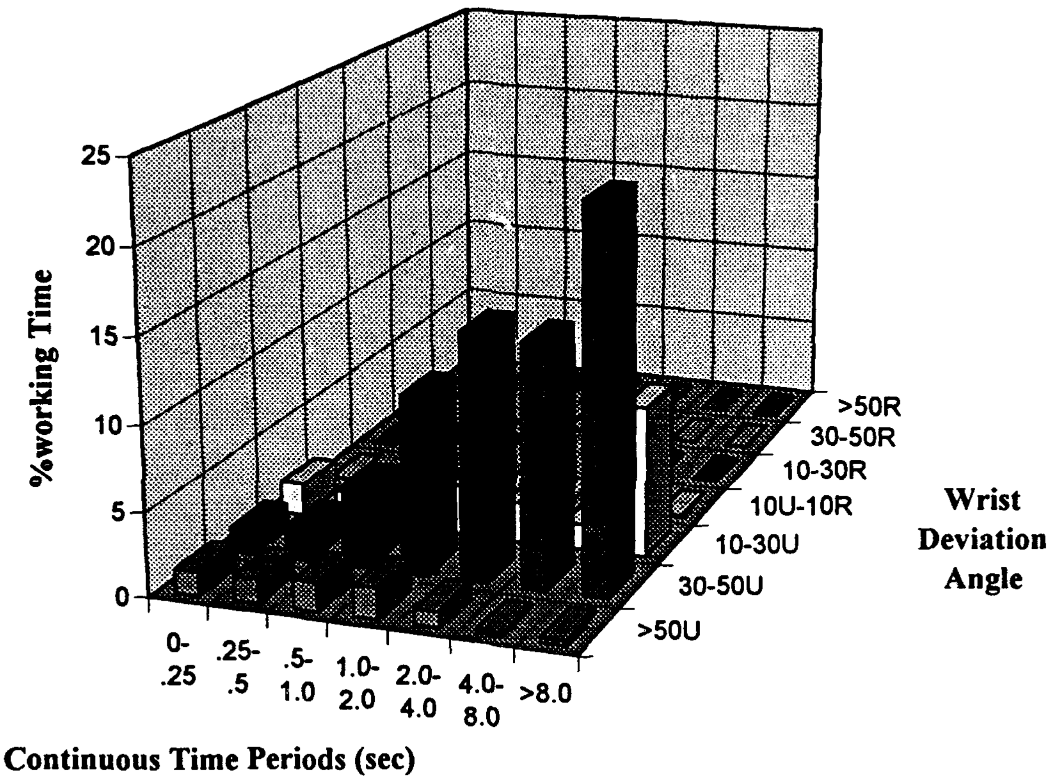

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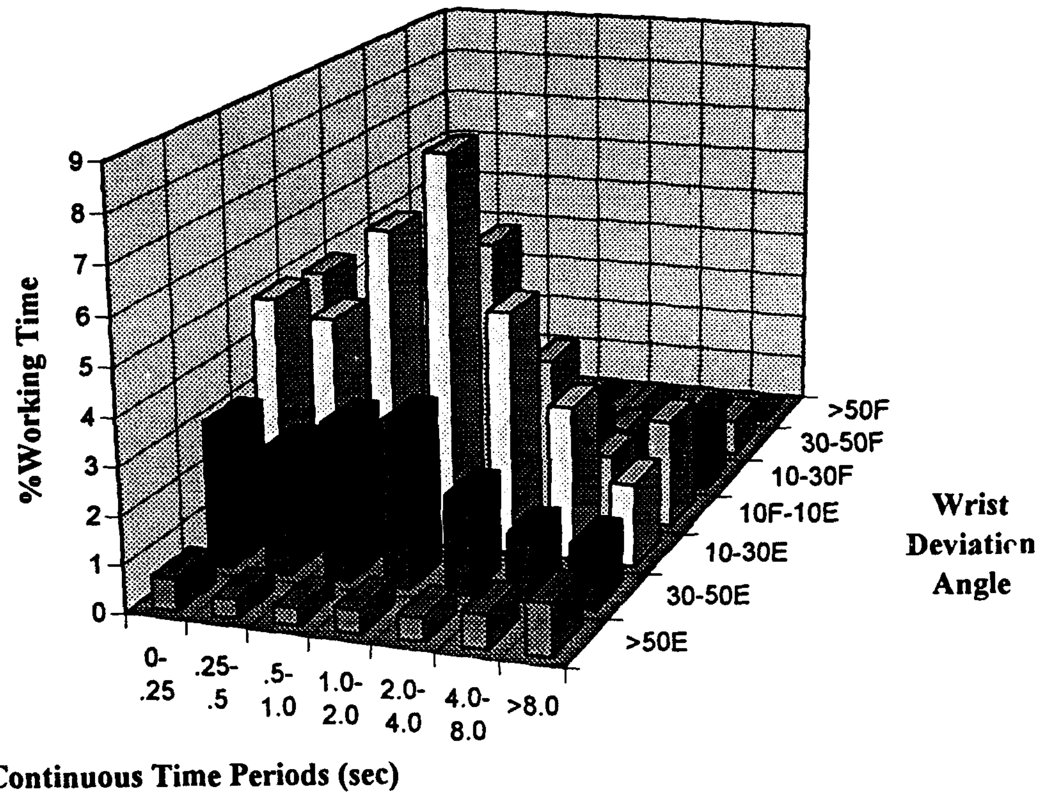

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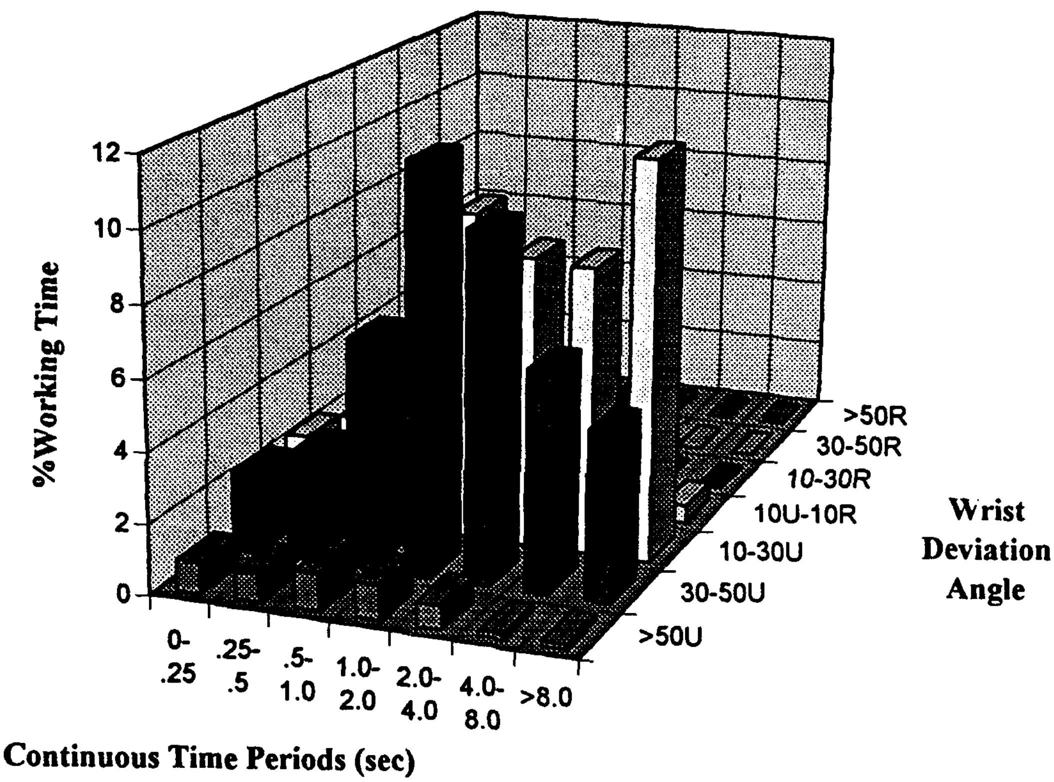

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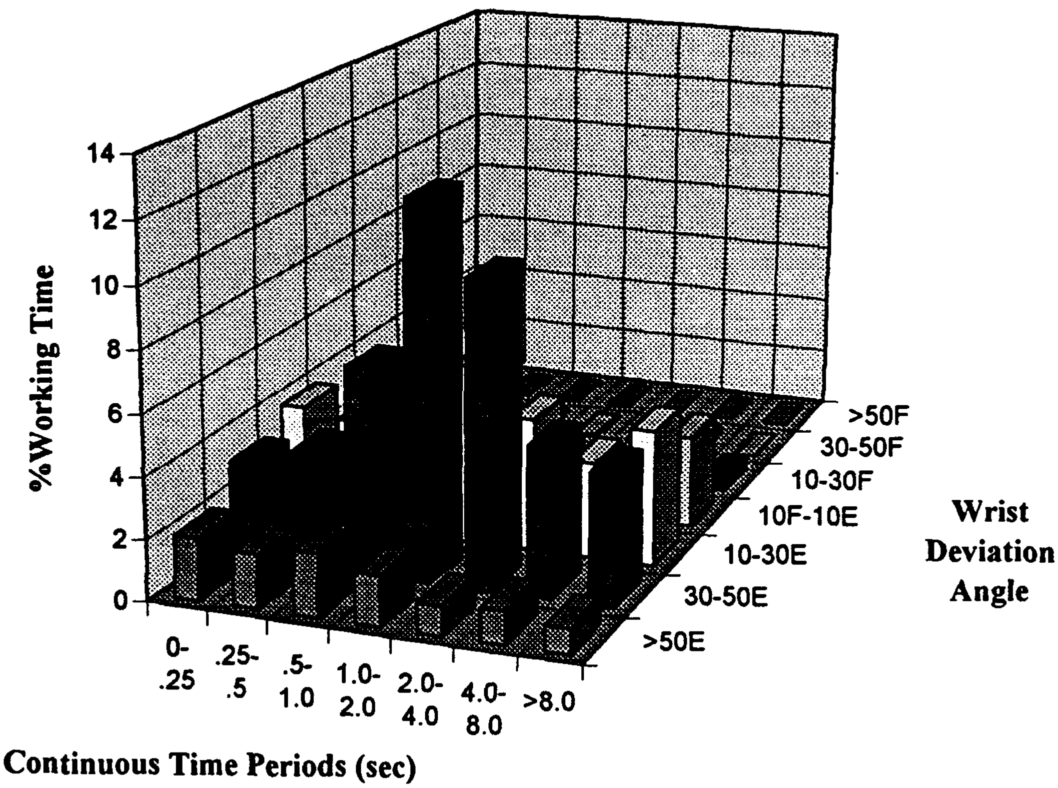

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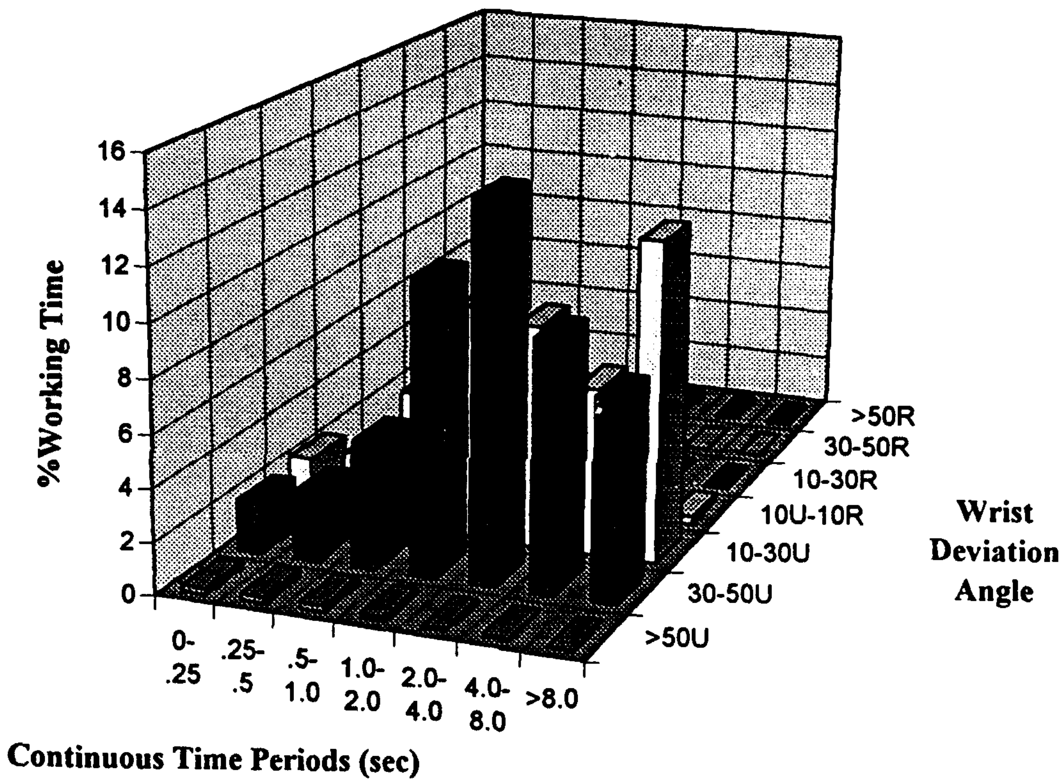

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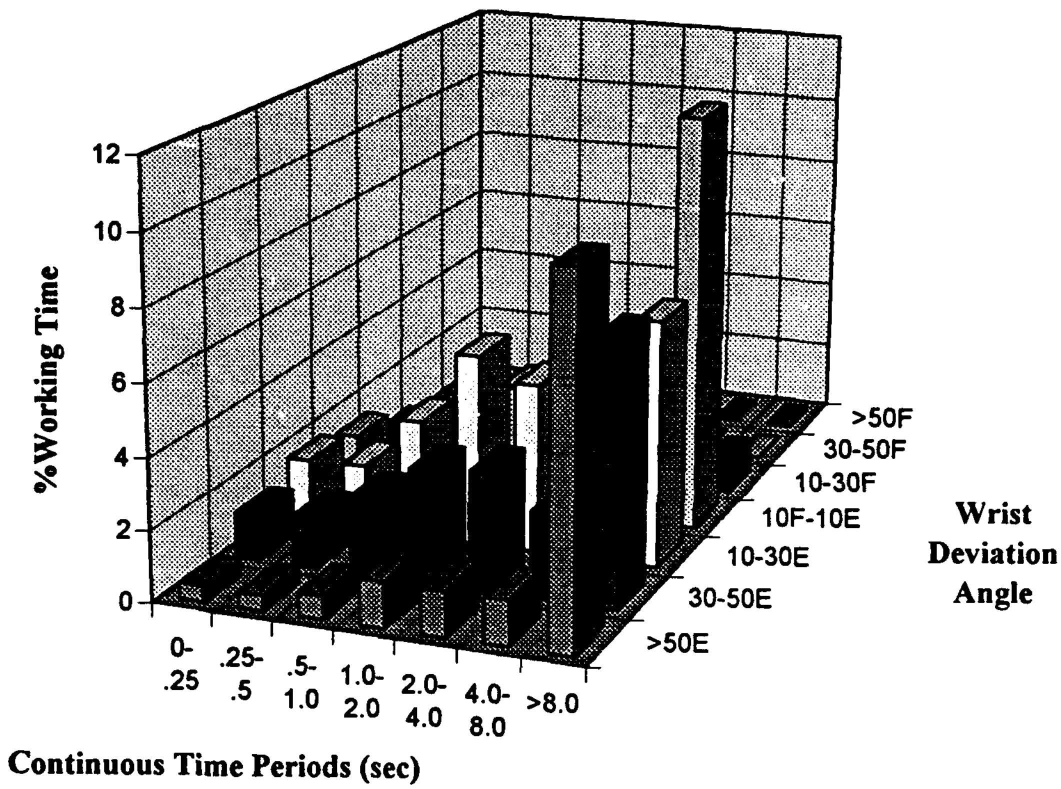

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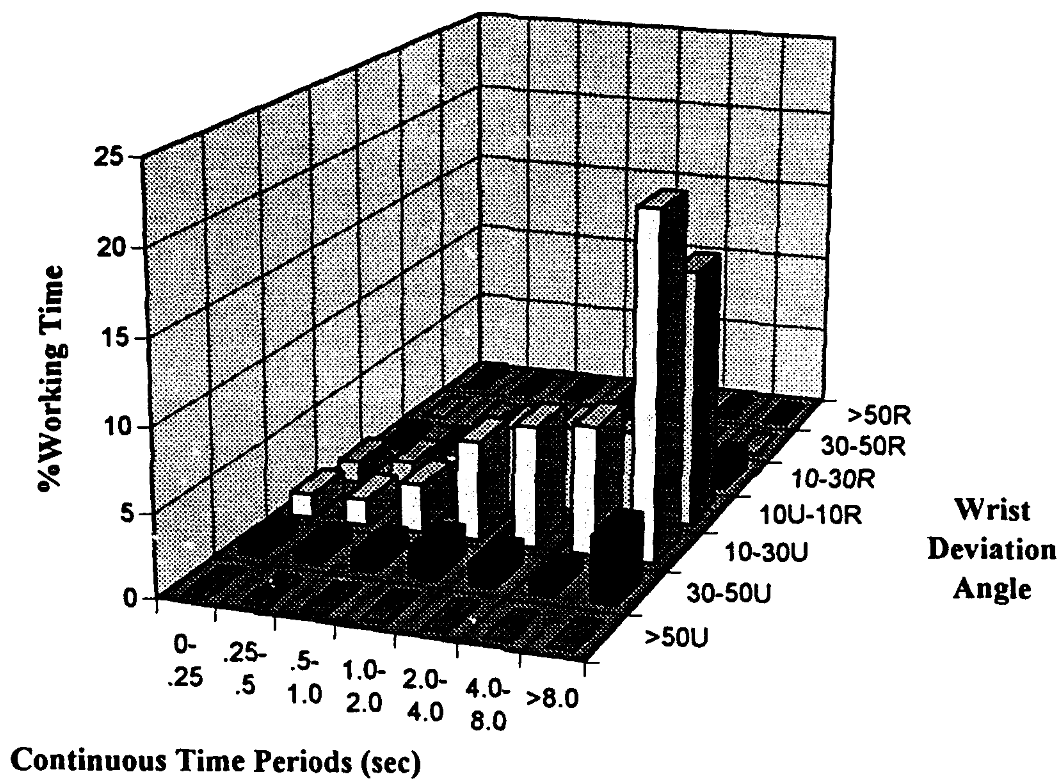

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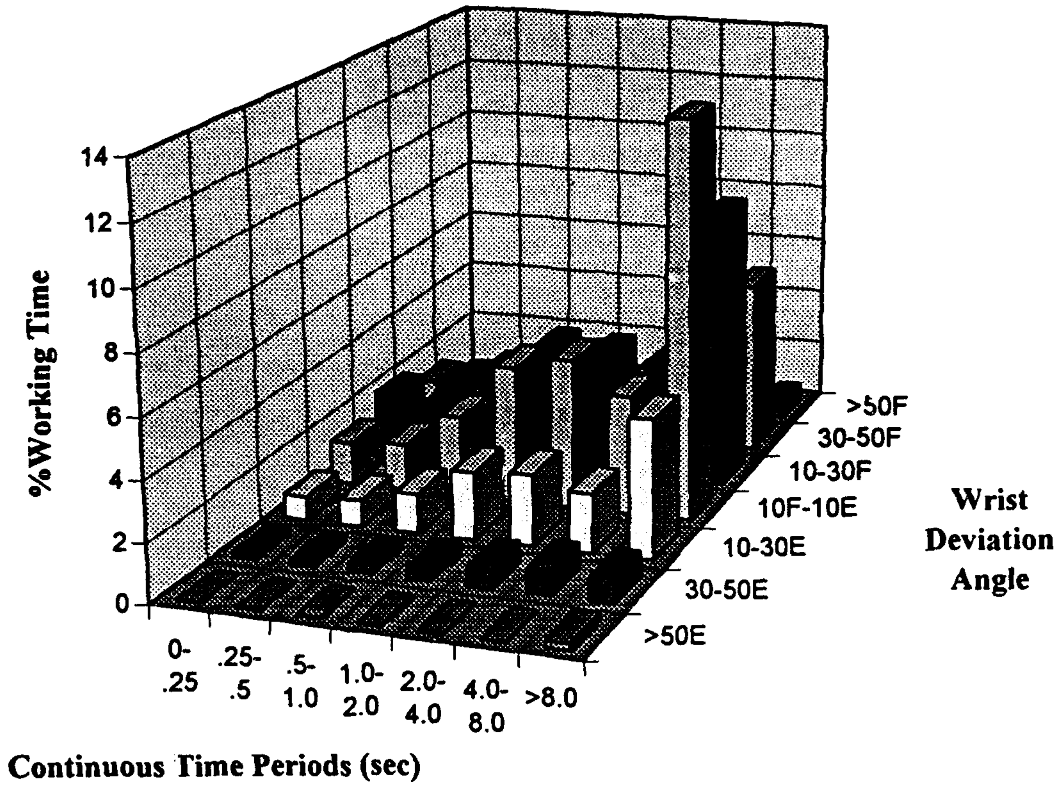

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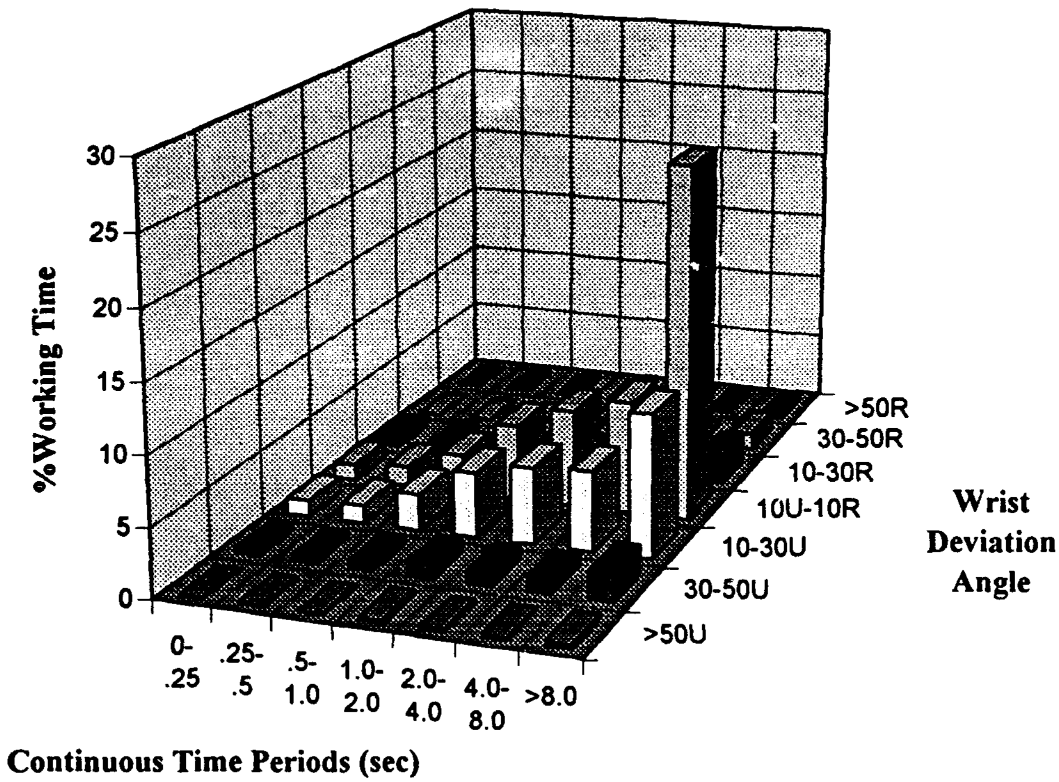

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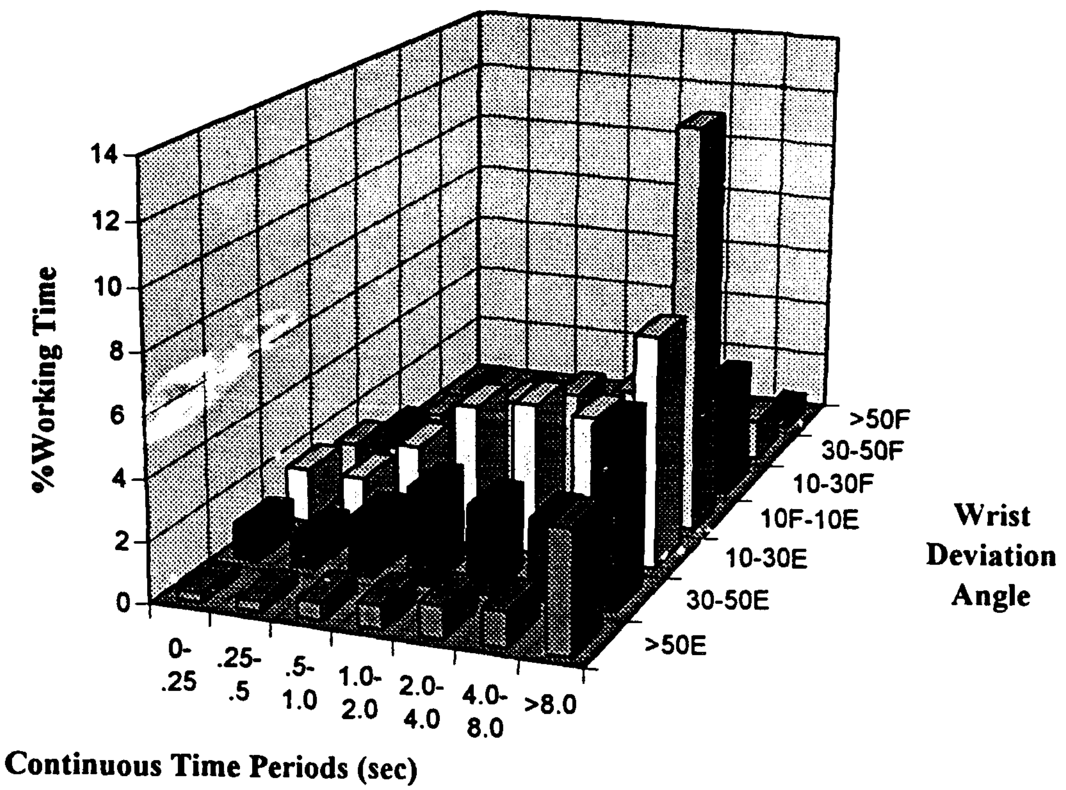

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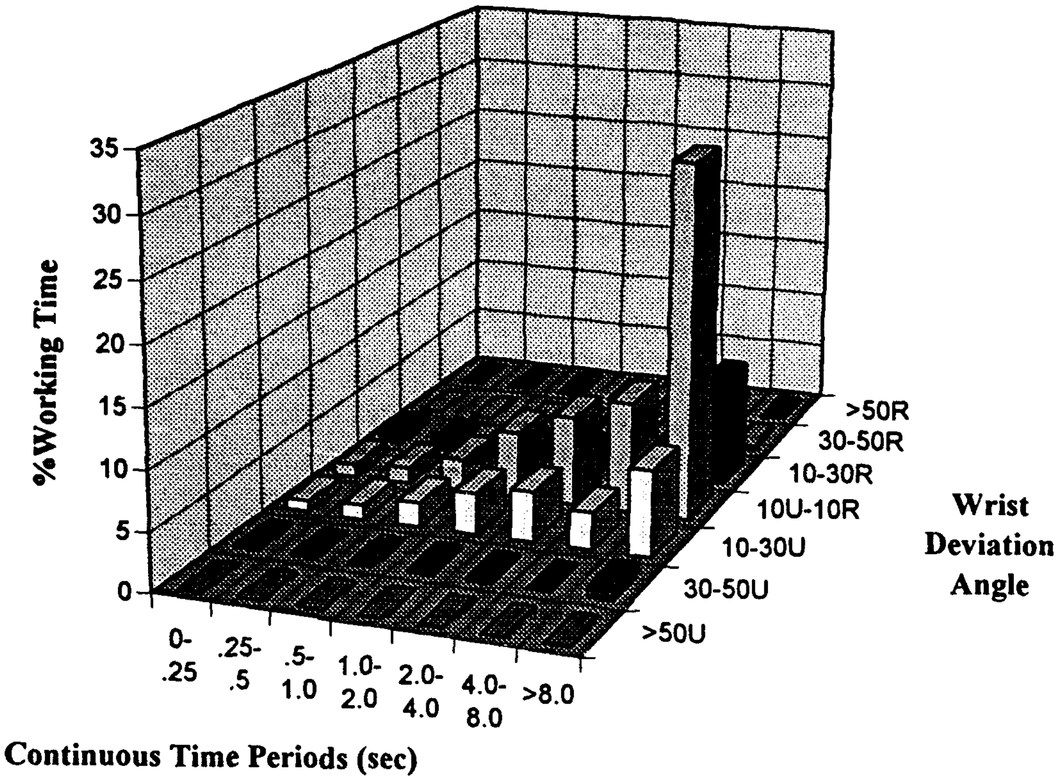

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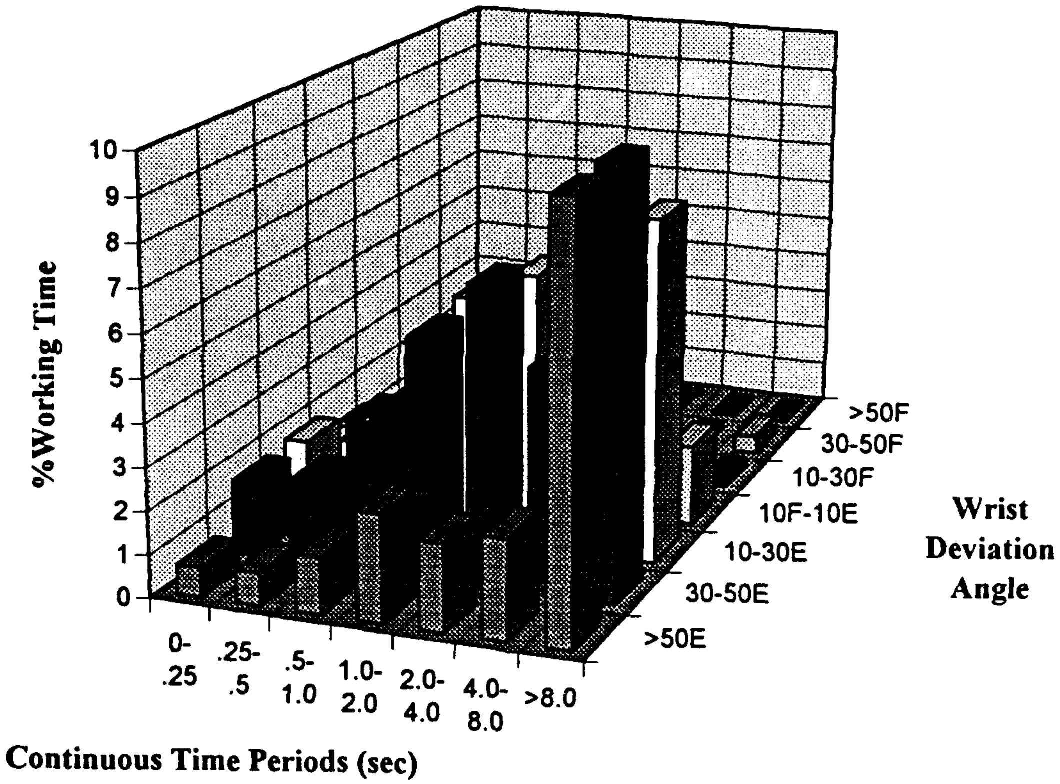

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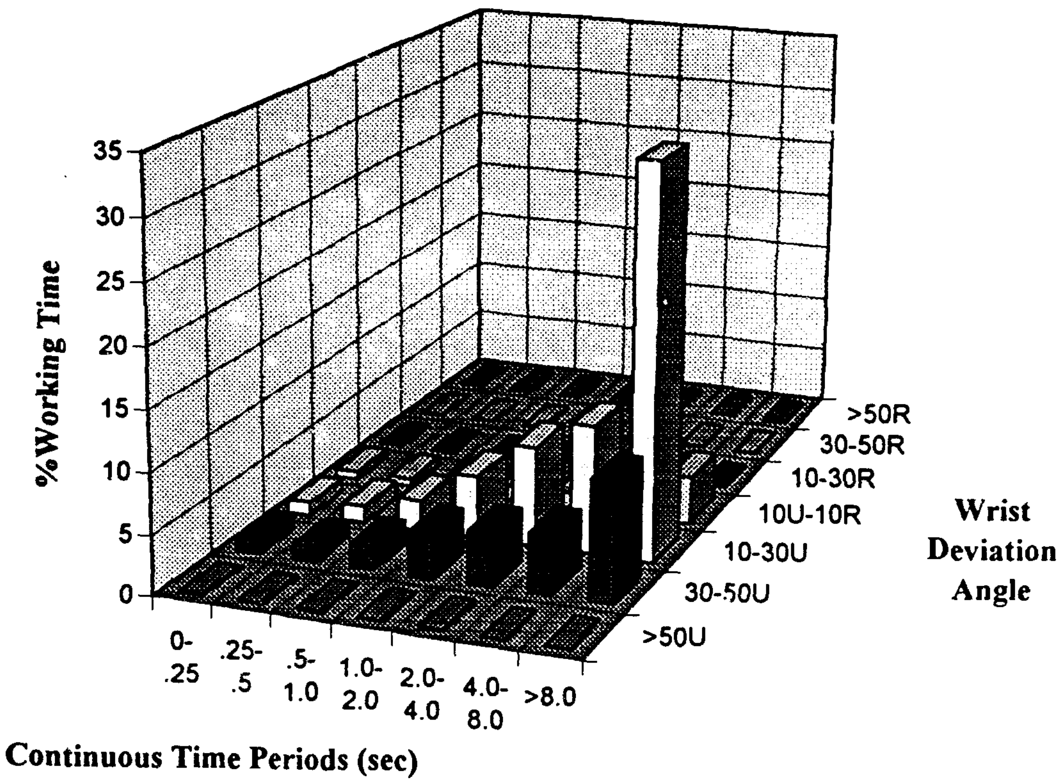

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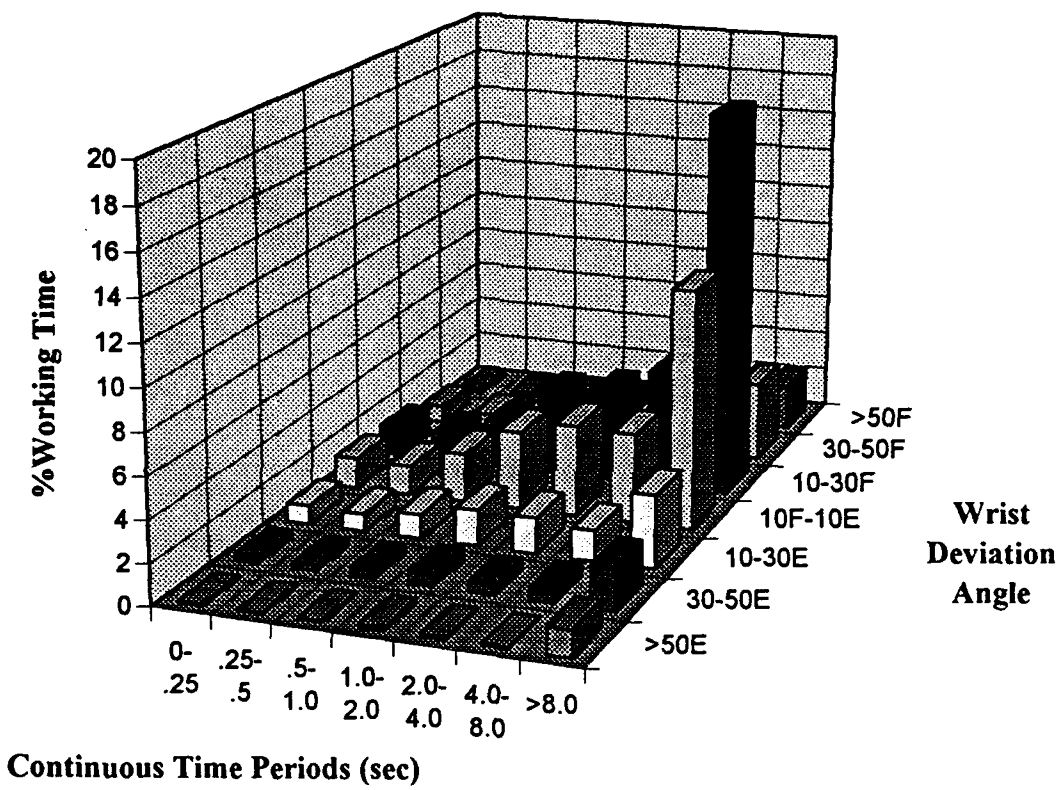

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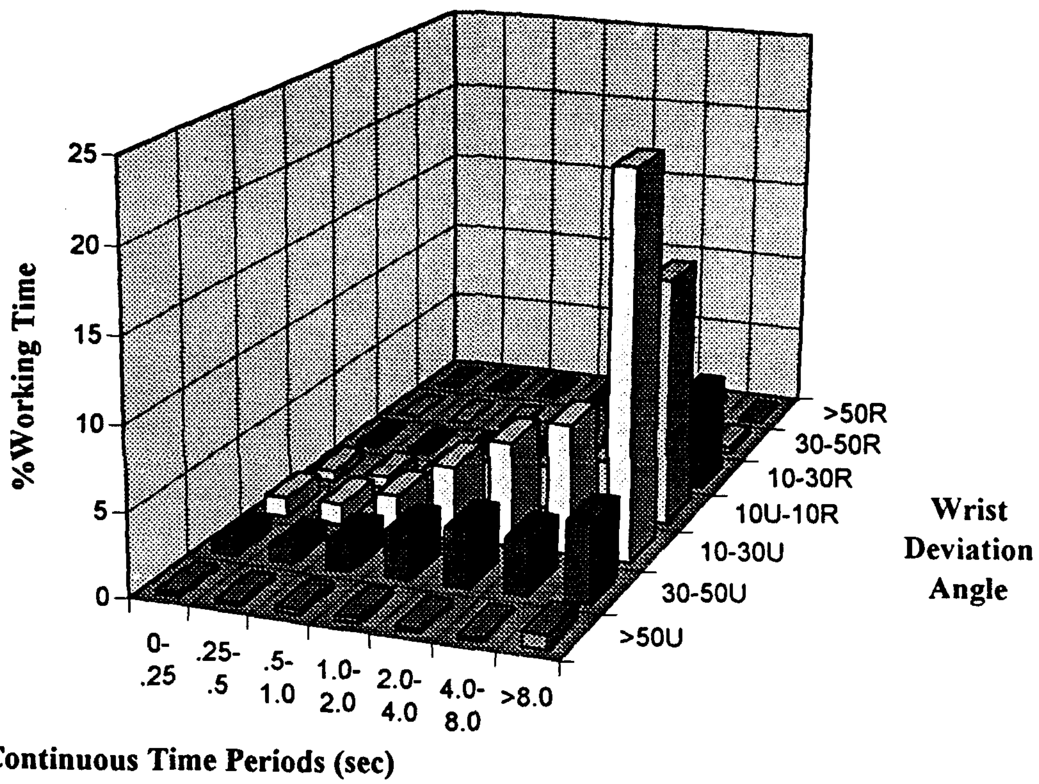

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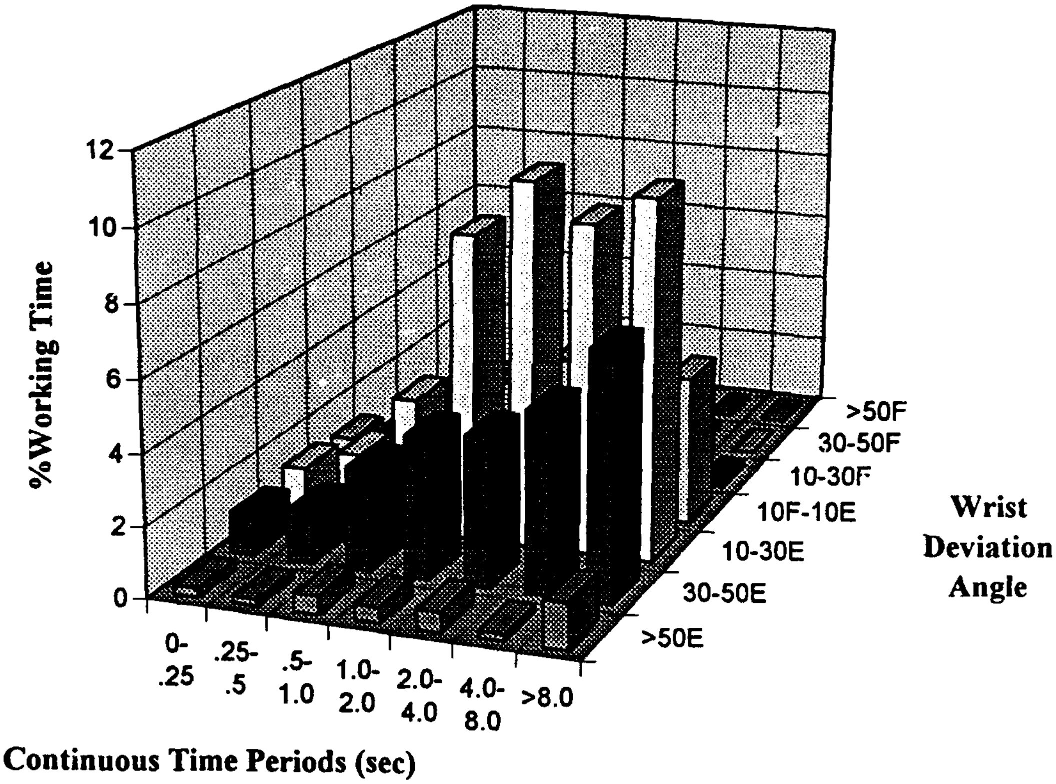

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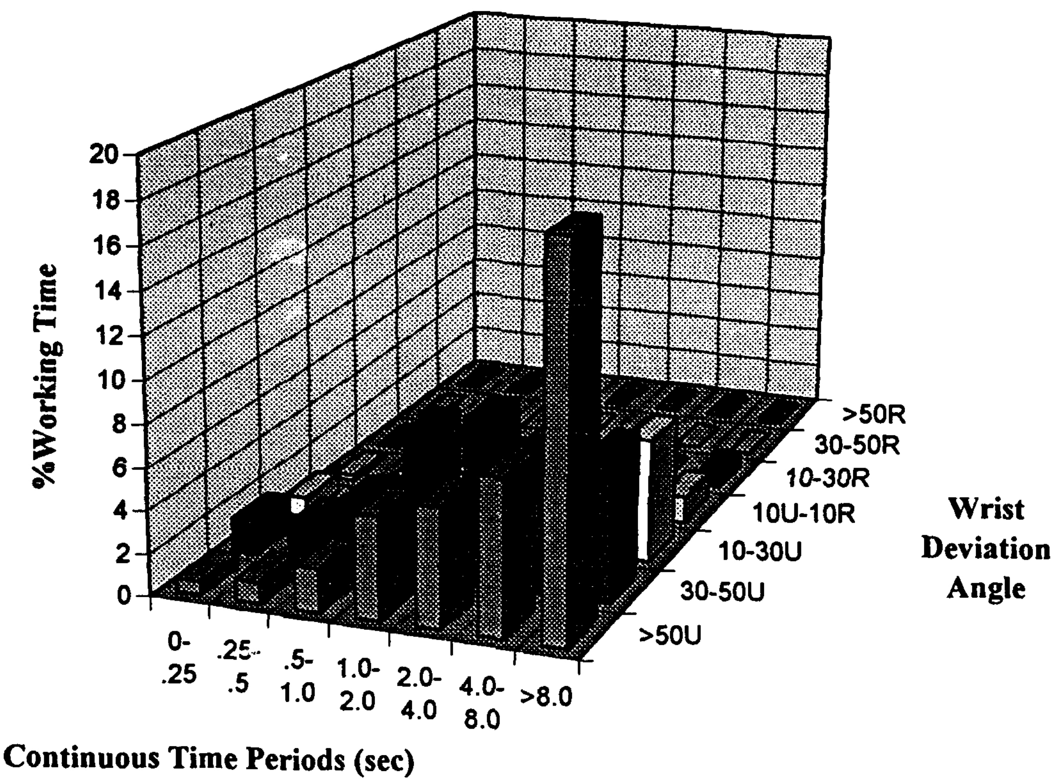

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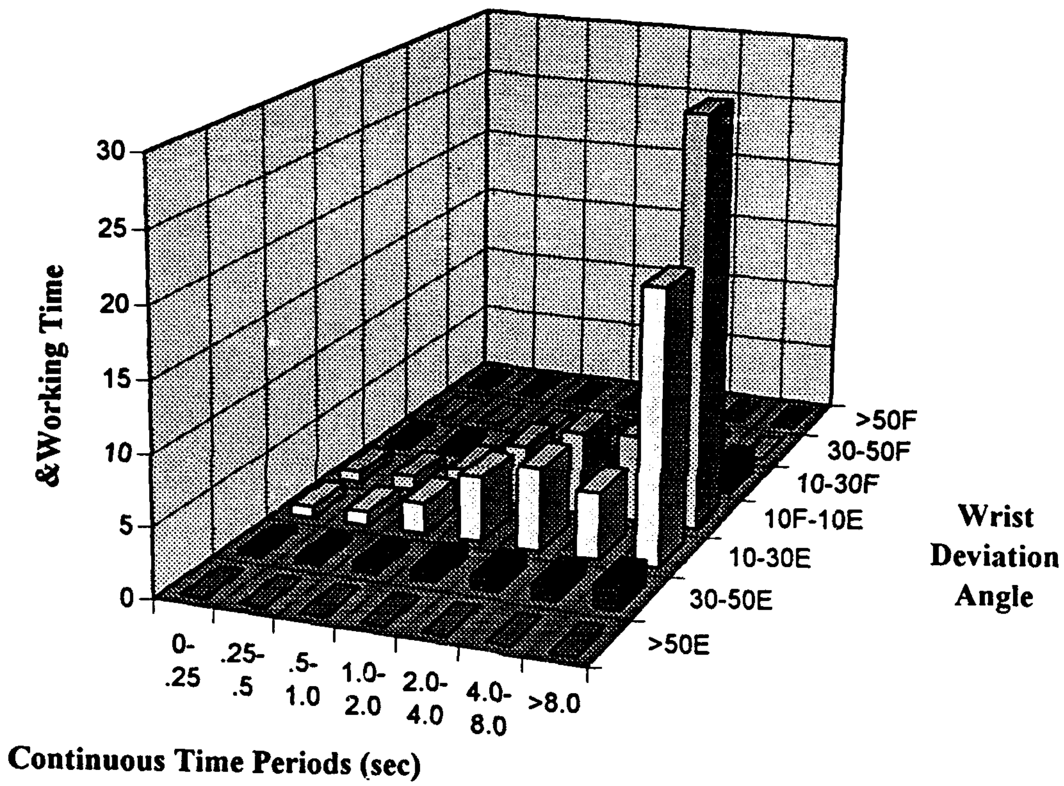

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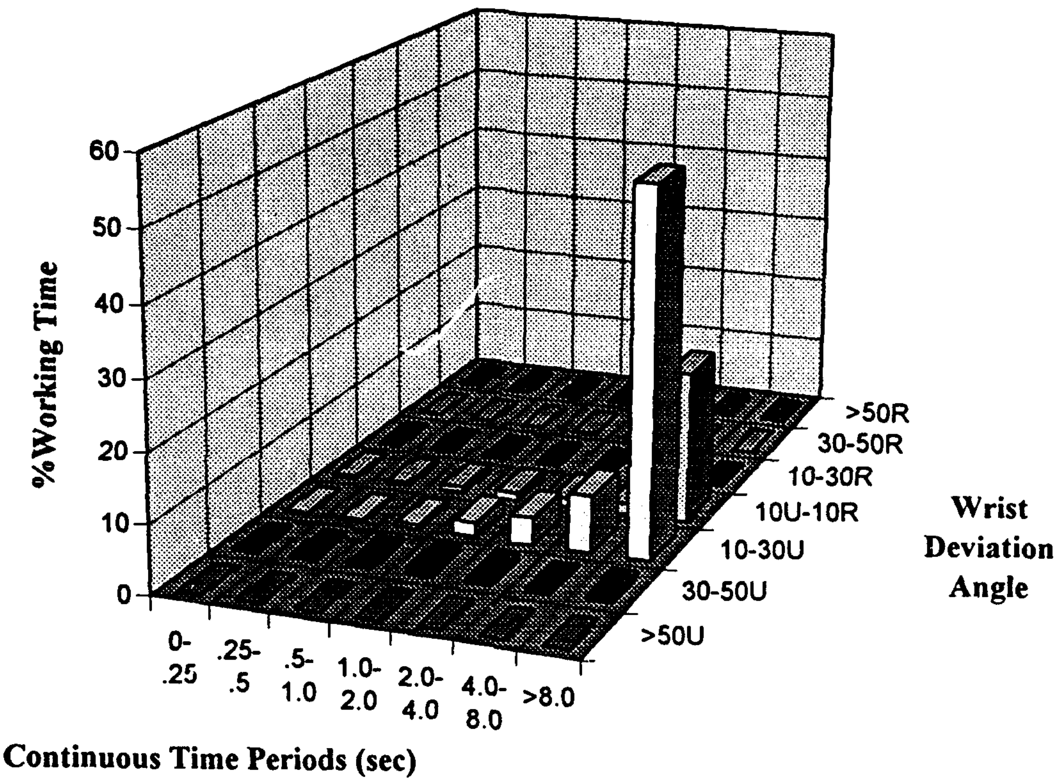

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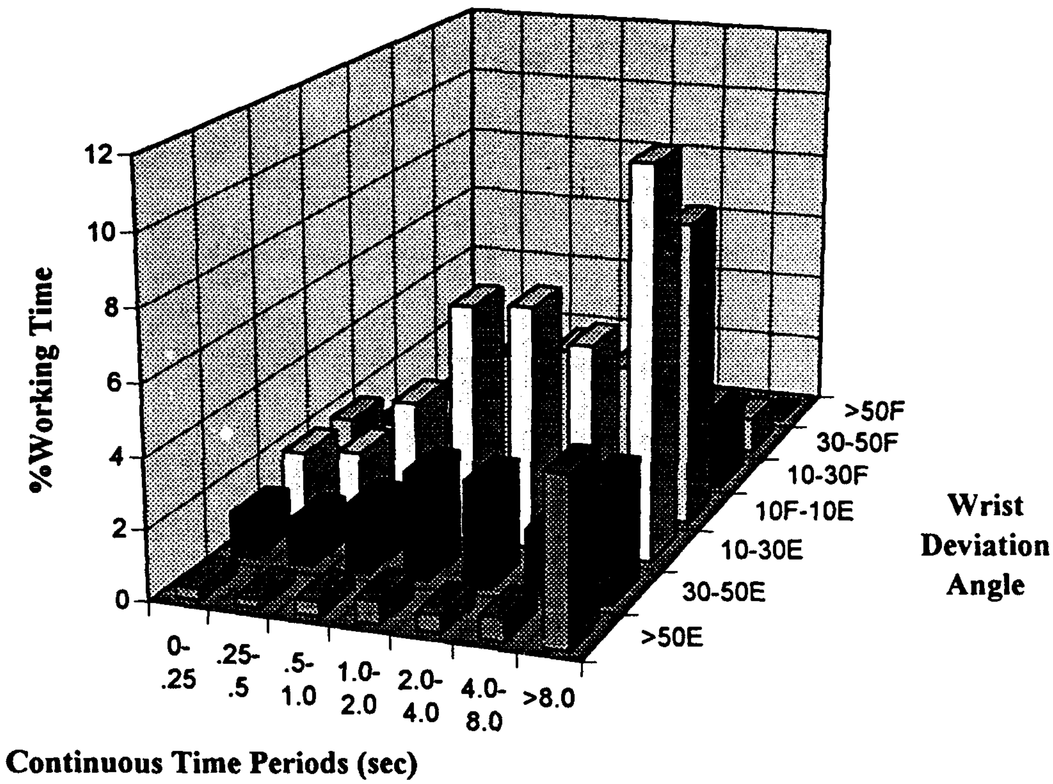

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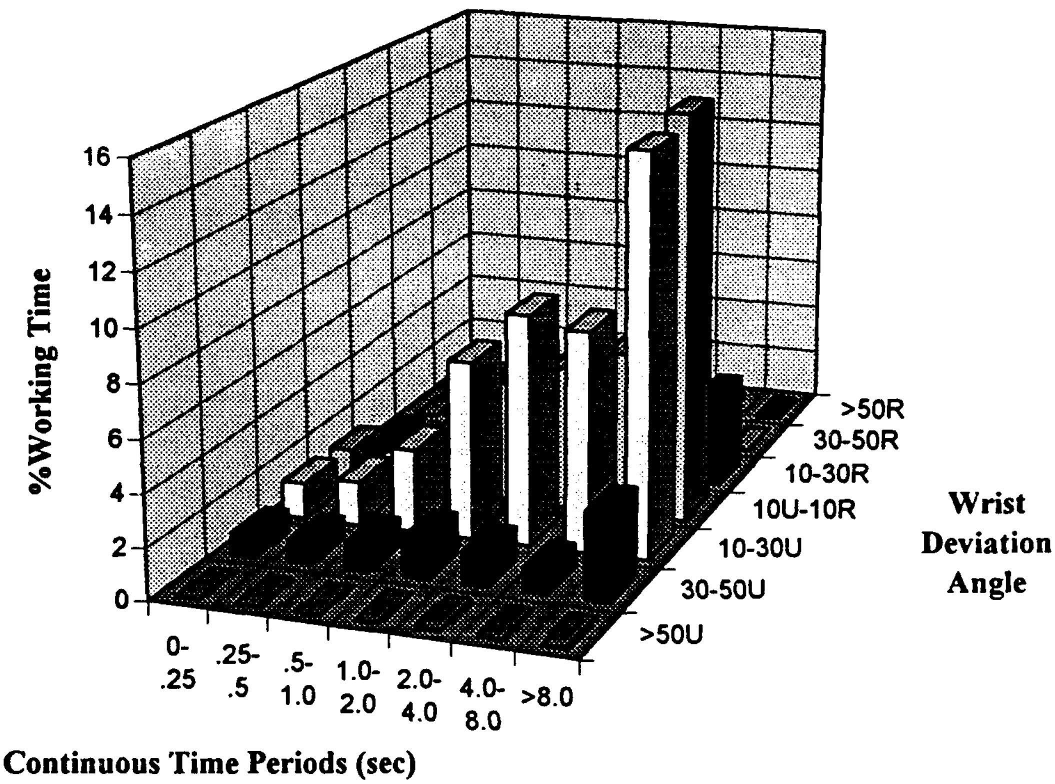

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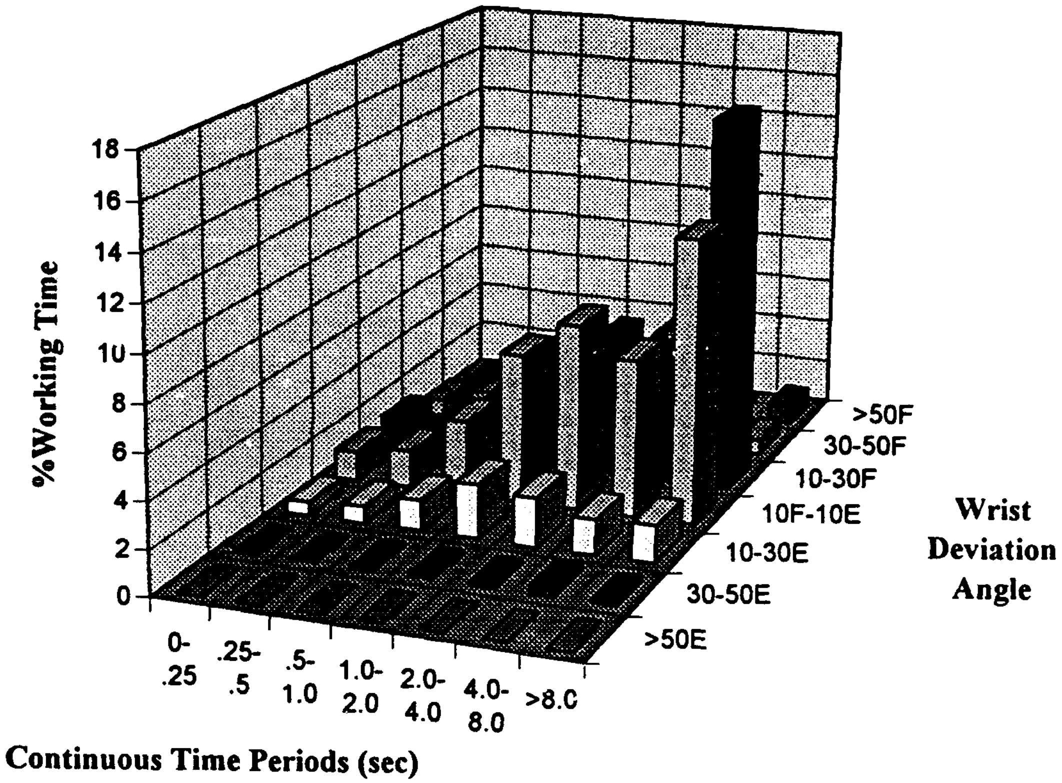

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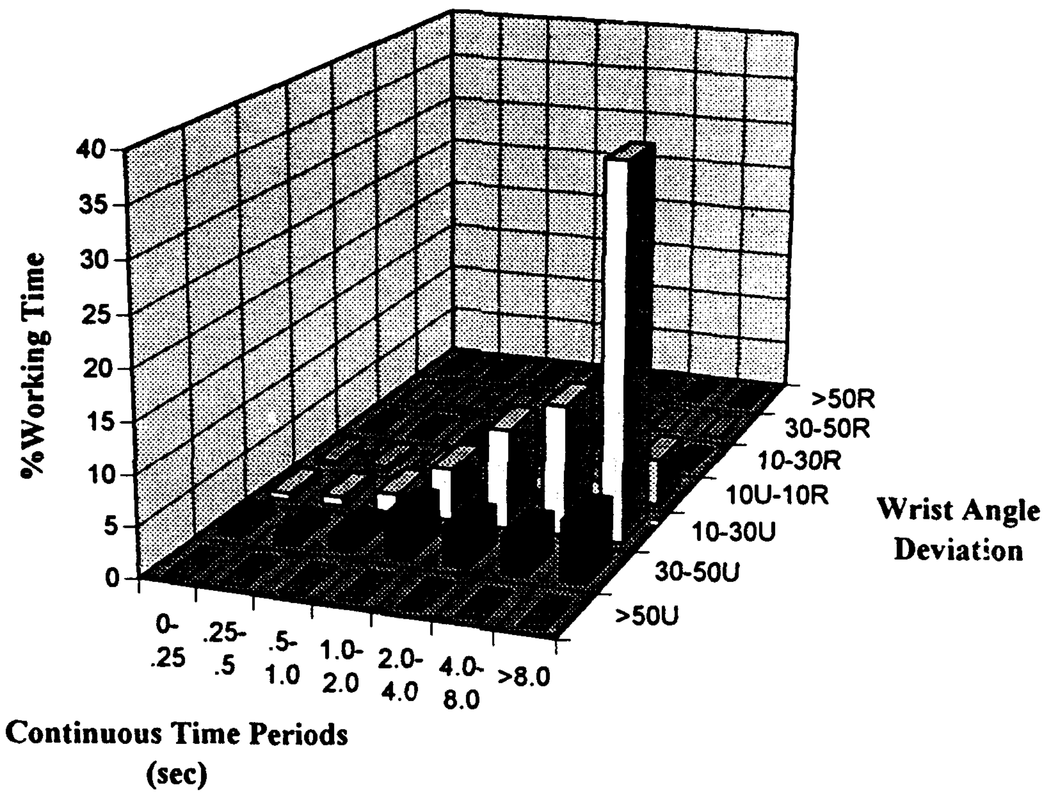

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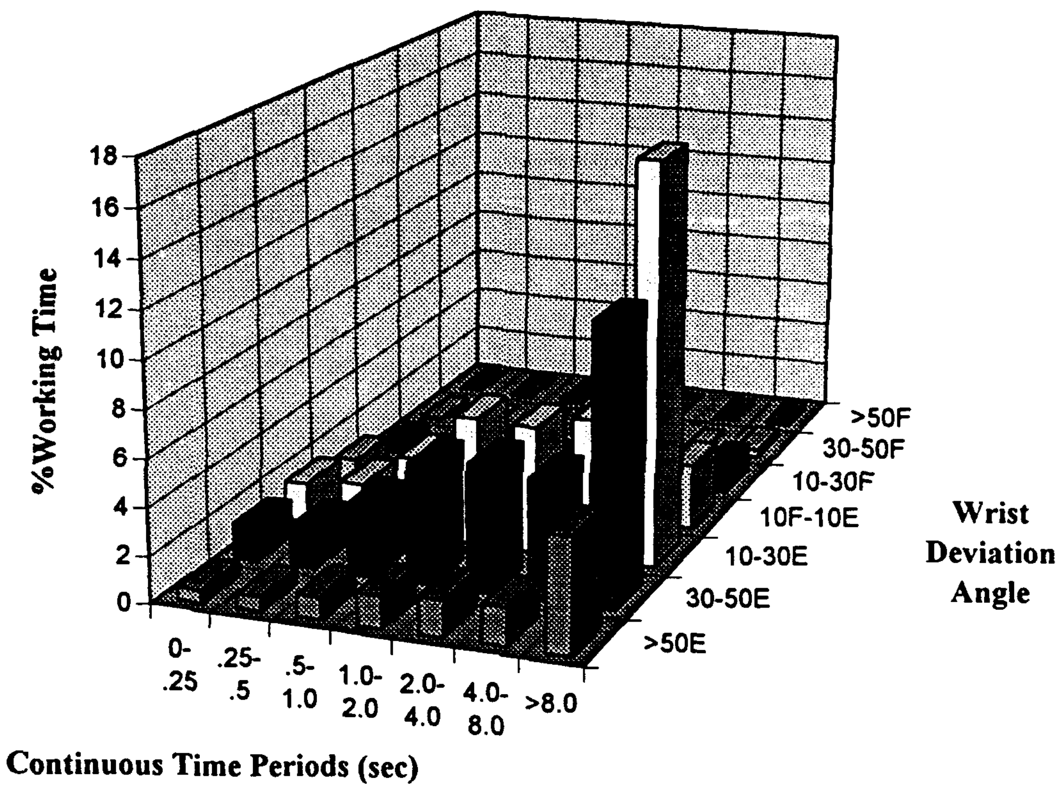

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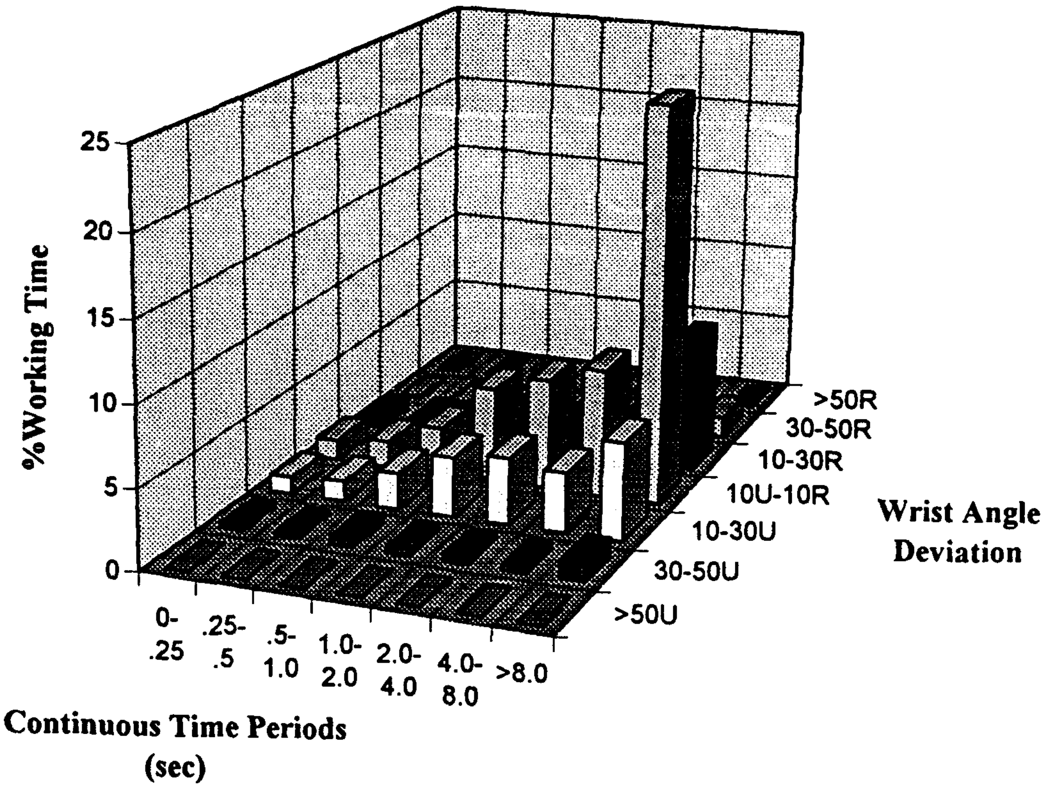

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